Karlsruher Institut für Technologie

ITEP – Institute for Technical Physics

Results of Research and Development
2021 Annual Report

IMPRINT

Karlsruhe Institute of Technology (KIT)
Institute for Technical Physics
Hermann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen,
Germany

Phone +49 721/608-23 501
www.itep.kit.edu

TEXTS:
Tabea Arndt, Giovanni De Carne,
Christian Day, Thomas Giegerich,
Francesco Grilli, Jens Hänisch,
Bernhard Holzapfel, Frank Hornung,
Ingeborg Meyer, Mathias Noe,
Stylianos Varoutis, Klaus Weiss,
Michael Wolf

Translation: KIT Translation Service

PHOTOS AND CHARTS:
Karlsruhe Institute of Technology (KIT)

COVER PHOTO:
View into the HERMESplus facility on
a hydrogen plasma at a cylindrical
superpermeation foil (Niob at 900°C)
(right side).

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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:

- **Superconducting and cryogenic materials**
- **Energy applications of superconductivity**
- **Superconducting magnet technology and**
- **Technologies of the fusion fuel cycle**

The work of the ITEP is anchored in the long term in the programmes „Fusion", „Materials and Technologies for the Energy Transition", „Energy System Design" 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 work on the complex and mostly multidisciplinary tasks, which are constantly adapted to the changing requirements and questions. These include, for example, a laboratory for the development of superconducting components for energy technology, a technical centre for the development of superconducting materials, the magnet laboratory for the development of specific superconducting windings and magnets, the cryogenic high-voltage laboratory for investigating the high-voltage strength of cryogenic insulating materials and the cryogenic material laboratories for investigating electrical and mechanical properties at very low temperatures.

In 2021, our institute achieved very nice scientific results, a large number of successful development projects and some special challenges and events, which we will briefly discuss below.

In the **research field of superconducting and cryomaterials,** the investigation of new superconductors is an important focus of research. In 2021, the pinning mechanisms on novel NdFeAsO layers were investigated in collaboration with Nagoya University. In the process, the importance of grain boundary triplets for pinning was elucidated. As part of a joint aeronautics research project to develop hybrid designs for high-performance electric motors, additively manufactured materials were comprehensively thermophysically characterised for use in cryogenic electric motors in aircraft in a hydrogen environment. Furthermore, the entire pilot production of high-temperature superconductors from Bruker was transferred to KIT within the framework of a new and long-term cooperation with CERN. This will enable the production of research-specific tape architectures in application-relevant lengths in the future.

In the **research field of energy technology applications,** an important milestone was reached in a joint project for the development of a superconducting industrial busbar with a current strength of 200,000 amperes. A test with two modular partial conductors, each with 20,000 amperes, was successfully carried out. In the cryogenic high-voltage laboratory, a 10 kV bushing was used as an example to show that conventional RIS bushings are basically suitable for use at low temperatures. In another joint project for the development of a very compact 110 kV, 500 MVA superconducting cable for the city centre of Munich, the cable system was modelled very precisely electromagnetically and thermally. In our power hardware-in-the-loop laboratory, a 60 kW flywheel mass storage unit and a 3.5 kW micro gas turbine were modelled in real time and experimental validation was carried out in the laboratory. This means that very accurate real-time models are available for both components.

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, sample coils with superconducting strips only 2 mm wide were designed and fundamentally characterised. 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 successfully tested in our FBI laboratory with a current of 6 kA at a temperature of 4.2 K and a magnetic field of 12 T. In our winding laboratory, a robotic winding technology with three multi-axis robots was put into operation and the first sample coils were wound. In the future, the production of superconducting 3D coils is planned there. As part of the German government's hydrogen initiative, a very large joint project on the production, transport, storage and use of liquid hydrogen was launched.

In the **research field of fusion fuel cycle technologies,** we are developing fundamentally new vacuum technologies and processes for tritium extraction and recovery. The work package „Tritium Matter Injection Vacuum" in the new European fusion programme from 2021 to 2027 is off to a good start under the leadership of Mr Day. The manufacture of the cryopumps for the JT-60SA fusion facility was awarded to an industrial partner and we will continue to support it. For the complex divertor of the W7-X fusion experiment, a complete fluidic simulation was carried out in a reasonable computing time. In the research field of vacuum hydraulics and hydrogen separation, extensive tests were carried out on our mercury test pumping station and the results used to upscale DEMO's pumping capacity. The „Direct Internal Recycling" method developed at the Institute for DEMO's fuel cycle is now also being set up on a large scale. For this purpose, the „Direct Internal Recycling Development Platform Karlsruhe", (DIPAK) was approved by the KIT presidium. This facility replicates two of the three circuits of the in the fuel cycle and contains all new technologies such as pellet injection, metal foil pumps, mercury pumps and temperature swing absorption for isotope separation.

In education, a total of 32 doctoral students were supervised by members of our institute in 2021, as well as 9 master's students and 13 bachelor's theses.

In 2021, the Corona pandemic posed many unusual challenges and we would like to take this opportunity to sincerely thank all our staff and all our cooperation partners from universities, research institutions and industry for their understanding of the numerous restrictions and their prudence in taking the necessary measures. We look forward to further cooperation in 2022 and wish you all the best.

Yours sincerely

Mathias Noe

Bernhard Holzapfel

Tabea Arndt

Results from the Research Areas

"Delivery of HTS R&D pilot line components as part of the ongoing KC4 collaboration with CERN."

Superconducting- and Cryo-materials

Coordination: Prof. Dr. Bernhard Holzapfel

The understanding of superconducting materials and the characterization of material properties at cryogenic temperatures as well as the realization of conductor structures form the basis of any superconducting energy or magnet application. Therefore, ITEP is currently working on the following research topics in the research field of superconducting and cryogenic materials:

- Superconducting Materials
- Conductor and cable technologies
- Structural and functional materials for cryogenic applications

SUPERCONDUCTING MATERIALS

Zu den Schwerpunkten dieses Forschungsthemas gehören sowohl grundlegende festkörperphysikalische und materialwissenschaftliche Fragestellungen, wie das Verständnis und die Verbesserung der elektrischen Transporteigenschaften etablierter Supraleitermaterialien, als auch anwendungsorientierte Grundlagen-untersuchungen an neuen Supraleitern mit Anwendungspotential.

HIGH-TEMPERATURE SUPERCONDUCTORS

In the field of high-temperature superconductors, we have continued our investigations on the optimization of chemical solution deposition and the systematic studies on the rare earth RE in $REBa_2Cu_3O_7$ compounds. To optimize the critical temperature T_c of TFA-MOD-grown $REBa_2Cu_3O_7$ thin films, several process parameters such as crystallization temperature Tcrys, oxygen partial pressure p_{O2}, total pressure p_{tot}, dew point T_{dew} and residence time τ need to be adjusted.

A new method in the field of statistical design of experiments (DOE) is Definitive Screening Design (DSD) [1], in which each parameter is set at three levels (high, medium, low). DSD allows estimation of 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 number of experiments needed as much as possible. We use this method to optimize the self-field critical temperature Tcsf for $ErBa_2Cu_3O_7$ thin films on CeO_2-buffered IBAD substrate, Fig. 1. $REBa_2Cu_3O_7$ films with different rare earths, both pristine and with $BaHfO_3$ nanoparticles added, were systematically studied in static and pulsed high-field magnets in collaboration with research groups in Nagoya, Tohoku, and Toulouse. The measurements of the anisotropy in the critical current density Jc with respect to the magnetic field orientation of $SmBa_2Cu_3O_7$ films in static fields up to 25 T continued our last year's work on $GdBa_2Cu_3O_7$ films [2], Fig. 2. Interestingly, due to the already complex microstructure in $SmBa_2Cu_3O_7$ films, the $BaHfO_3$ nanoparticles have little effect on Jc here (in contrast to other rare earths).

The critical fields of nine different $REBa_2Cu_3O_7$ layers could be determined resistively in pulsed fields up to 60 T within one week (record!). For this purpose, not only the film growth for the corresponding systems was optimized in advance by means of pulsed laser deposition and chemical solution deposition, but also structuring, contacting and sample preparation. With RE = Sm, Dy, and Ho, we chose $REBa_2Cu_3O_7$ systems with a very

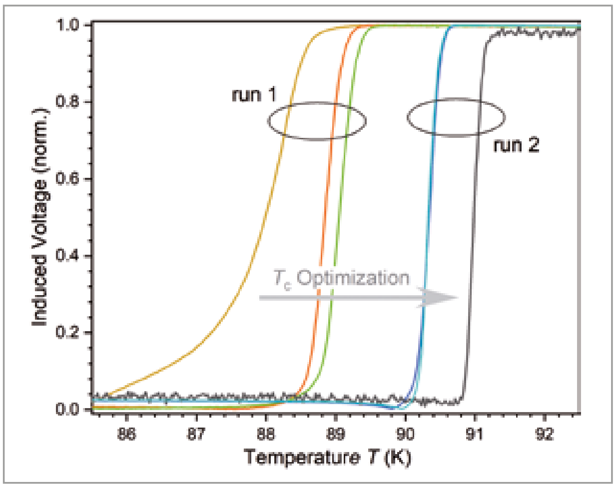

Fig. 1. Inductively measured superconducting transition of multiple $ErBa_2Cu_3O_7$ thin films on CeO_2-buffered IBAD substrate during DSD optimization of critical current density T_c.

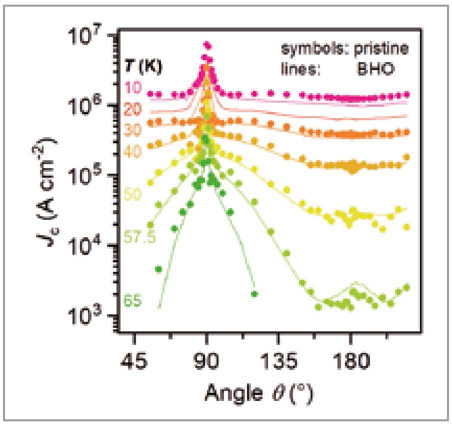

Fig. 2. Anisotropy of the critical current density of $SmBa_2Cu_3O_7$ without (symbols) and with (lines) $BaHfO_3$ nanoparticles at several temperatures in a 24 T magnetic field.

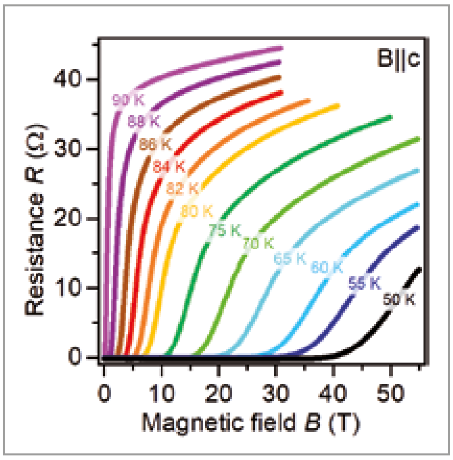

Fig. 3. Magnetic field dependence of the electrical resistance of a BaHfO3-$SmBa_2Cu_3O_7$ nanocomposite thin film in fields up to 55 T

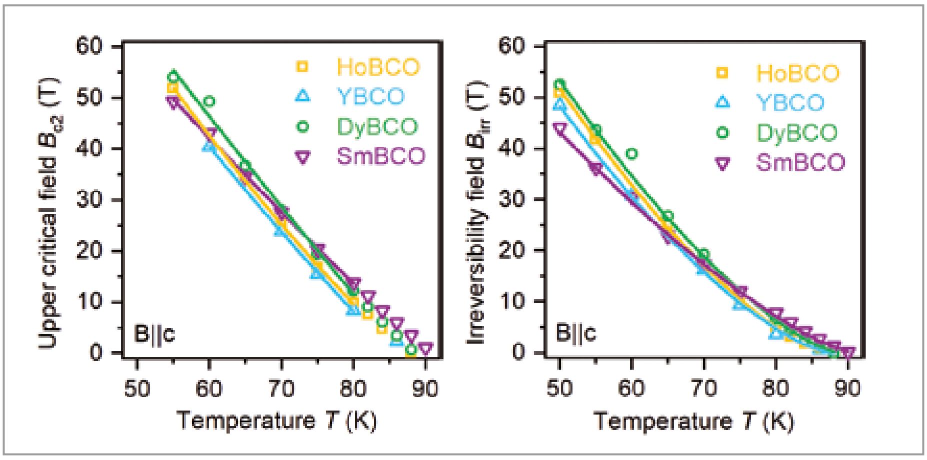

Fig. 4: Comparison of the upper critical fields Bc2 (left) and irreversibility fields Birr (right) for different pristine $REBa_2Cu_3O_7$ thin films.

wide range of RE ion sizes in order to compare them to the well-studied $YBa_2Cu_3O_7$ system, Fig. 3 and 4.

Nanoscale impurity phases or defects in REBCO thin films can improve the current-carrying capacity. In collaboration with the Laboratory of Electron Microscopy (LEM) at the South Campus, we apply scanning transmission electron microscopy (STEM) for microstructural investigation. High-angle annular dark-field (HAADF) STEM imaging directly reveals the atomic structure because in HAADF-STEM the image intensity directly correlates with the average atomic number, making heavier elements appear brighter. Thus, plate-like precipitates in GdBCO layers could be initially localized at medium magnification in a cross-section sample (Fig. 5A) and identified as Gd2CuO4 based on the atomic structure (Fig. 5B). The crystal structure of Gd_2CuO_4 is similar to that of GdBCO, so that the impurity phase is coherently incorporated – that is, without the formation of further lattice defects – in the GdBCO layer. The Gd-rich (and Ba-depleted) Gd_2CuO_4 precipitates were also confirmed by electron energy loss spectroscopy (EELS) chemical analysis (Fig. 5C), as the precipitates show an enhanced/reduced Gd/Ba signal. The periodicity of around 1.2 nm of the Gd and Ba signals in GdBCO corresponds to the lattice constant in the growth direction.

The optimization of REBCO thin film structures requires the study of many fabrication parameters and TEM samples. However, sample preparation for STEM and subsequent STEM examination in different instruments is time consuming. In modern scanning electron microscopes (SEM) with a focused-ion -beam (FIB) system, sample preparation and STEM imaging can be combined in one instrument, which accelerates the microstructural investigation [Y]. As an example, Figure 5D shows a STEM image taken in an SEM (STEM-in-SEM) of a GdBCO layer in top view. Here, the distribution of impurity phases can be investigated. In addition, twin boundaries can also be seen.

FE-BASED SUPERCONDUCTORS

In the field of Fe-based superconductors, we have collaborated with Nagoya University to determine the pinning properties of novel MBE-grown NdFeAsO films.
The H-substitution of oxygen in this com-

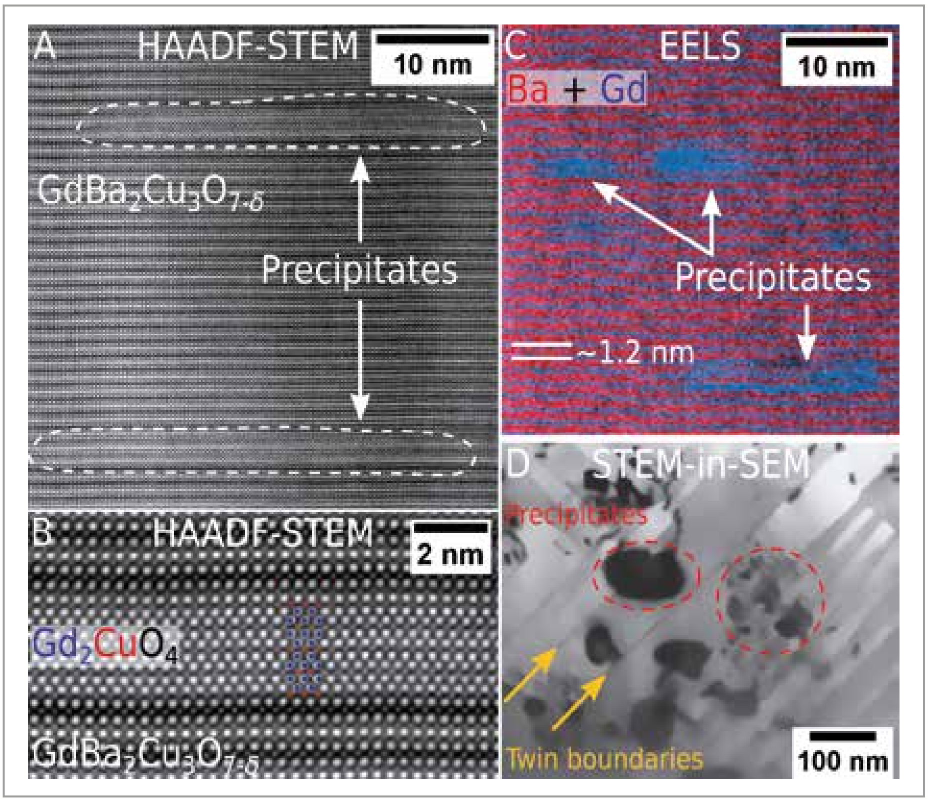

Fig. 5: (A,B) HAADF-STEM: cross-section of Gd_2CuO_4 impurity phases in GdBCO. (C) EELS: distribution of Ba (red) and Gd (blue). (D) STEM-in-SEM: top-view of a GdBCO thin film with impurity phases and twin boundaries.

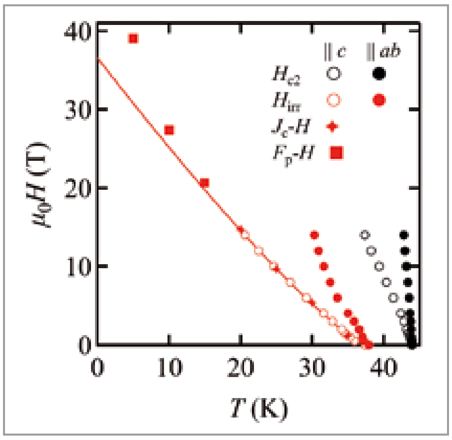

Fig. 6: B-T phase diagram of a NdFeAs(O,H) thin film with irreversibility field and upper critical field for both main crystallographic directions [4].

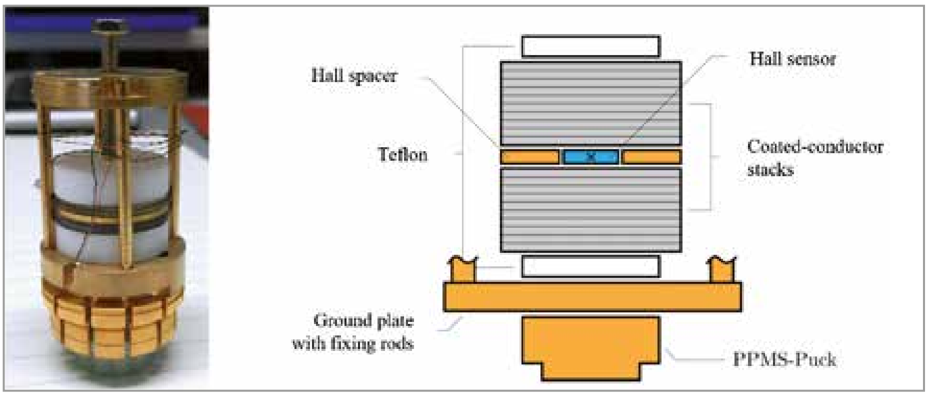

Fig. 7: Photo and schematic of the arrangement for measuring magnetization and creep behavior of coated-conductor stacks.

pound is characterized by a much larger substitution range than for the F-substitution. Such films have hardly been prepared and studied so far. From detailed transport measurements, we were able to establish both the phase diagram, Fig. 6, and to determine different magnetic field-temperature ranges for different pinning mechanisms (weak – strong, intrinsic – extrinsic, 2D – 3D, ...) [4].

F-doped NdFeAsO films on technical substrates, also grown by MBE in Nagoya, serve as evaluation tests for a possible application of these materials in coated conductors. On one of these samples, by combining transport measurements and detailed microstructural studies in transmission electron microscopy (Kyushu University), we were able to determine, in particular, the importance of grain boundary triple points for flux pinning in combination and interaction with other defect types [5].

TAPE STACKS

In recent years, tape stacks, i.e. stacks of short pieces of superconducting coated conductors, have become increasingly interesting as an alternative for melt-textured bulk samples, but also magnetic coils, for the generation of strong levitation forces or strong, homogeneous fields. We investigated the magnetization and creep behavior of such stacks in several undergraduate projects, both in magnetization measurements using a special measuring device suitable for the PPMS, Fig. 7, and with Comsol-programmed finite element simulations.

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Contact: Jens.Haenisch@kit.edu

CONDUCTOR AND CABLE TECHNOLOGIES

Within the scope of this research topic, we focus on the development of HTS conductor and cable architectures adapted to specific application scenarios, as well as their implementation on conductor/cable lengths that allow the realization of demonstrator applications.

R&D PILOT LINE FOR HTS COATED CONDUCTORS

A strategically longer-term research activity for the research area "Superconductor and Cryomaterials" developed in 2021 with the start of the construction of a complete HTS Coated Conductor synthesis line for the realization of complete conductor architectures for superconductor applications in energy and magnet technology. Central to these activities is the establishment of a long-term collaboration with CERN regarding the development of high current carrying and application specific HTS Coated Conductor architectures. The KIT-CERN Collaboration on Coated Conductor (KC4), which is initially scheduled for 5 years, includes the construction and operation of an industrial R&D synthesis line for the production of sufficiently long RE123 Coated Conductor architectures on the one hand, and on the other hand their consistent adaptation to application-specific requirements in magnet and energy technology applications such as HTS-based accelerator magnets or rotating machines. In doing so, KC4 can build on the highly successful Bruker work on the industrial synthesis of Y123 Coated Conductor for high field applications and will be able to use corresponding layer deposition equipment. The set-up of this complete RE123 R&D synthesis line required the rededication and conversion of about 500m2 laboratory space at ITEP last year, which was a major challenge especially under the current corona conditions and will be fully completed in 2022. A special highlight of the Bruker technology used is the currently internationally unique possibility to produce wide IBAD-based RE123 Coated Conductors up to 40mm tape width and RE123 foils up to dimensions of 30cmx100cm, thus enabling new research approaches for superconducting magnet and energy applications.

ESA HTS HARNESS – CURRENT LEADS FOR SUB-KELVIN-COOLERS ON SATELLITES

A number of future satellite missions within ESA's Cosmic Vision and Voyage 2050 program, e.g. ATHENA, will use instruments with extremely sensitive detectors that have to be cooled to temperatures below 1 Kelvin. Complex cryogenic chains with different types of coolers will be used to provide sufficient cooling power at different temperature levels. The lowest temperatures in the range of 50 – 100 mK can be reached with adiabatic demagnetization refrigerators (ADRs) which require strong magnets for the magnetization and demagnetization cycles. Due to the limited electrical power available on satellites, ADR magnets are usually operated with currents of only a few Amps. The current leads, which connect the power supply at a higher temperature stage to the magnet at the cold stage, are a major source of heat load. The use of superconductors can minimize this heat load.

Under an ESA contract, a power supply system based on 2nd generation high-temperature superconductors (REBCO coated conductors) capable of operating up to a temperature of 85 K with a rated current of 2 A and a maximum current of 5 A has been under development since 02/2021. The development work is funded under ESA's Technology Development Element (TDE) program, with Neutron Star Systems as the prime contractor. The Karlsruhe Institute of Technology is leading the technical development as subcontractor, while CEA Grenoble is responsible for the test campaign and Madrid Space for simulations.

The requirements set by ESA for the 1 m long harness include a flexible design allowing minimum bending radii of 50 mm in all spatial directions, a cable jacket for electrical insulation and humidity protection, electrical connectors to PhBr wires and NbTi wires at 85 K and 4 K, respectively, mechanical supports at temperature levels of 80 K and 30 K and a maximum

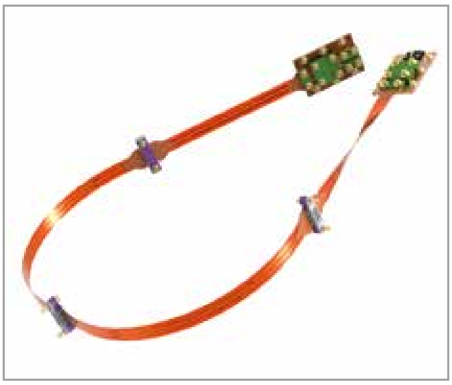

Fig. 8. Design of the ESA HTS current leads for sub-Kelvin coolers on satellites.

heat load of 1 mW at the cold end for the nominal current of 2 A. As part of the ESA contract, measurements of the properties of structural materials and REBCO tapes from various suppliers were performed and a Harness design was proposed: By laser cutting the width of the REBCO tapes will be adjusted to the thermal conductivity and current carrying capacity at the maximum operation temperature of 85 K. To protect the leads against moisture and provide electrical insulation, the REBCO tapes will be coated with Parylene C and then laminated with Kapton. For thermal coupling of the electrical connectors to the 85 K and 4 K levels in the cryostat thermally conductive and electrically insulating aluminum nitride (AlN) will be used. The mechanical supports at temperatures of 80 K will be made of thermally poorly conductive PEEK, while the support at 30 K is made of aluminum for thermal coupling. Model calculations by Madrid Space showed that KIT's proposed design (Figure 8) is capable of meeting the thermal and mechanical requirements. Fabrication of the Harness, as well as various tests at KIT and at CEA Grenobel, are planned for the first half of 2022.

Kontakt: bernhard.holzapfel@kit.edu

STRUCTURAL AND FUNCTIONAL MATERIALS FOR CRYOGENIC APPLICATIONS

MODERNIZATION OF FBI FACILITY COMPLETED

The development of superconducting cables for fusion magnets looks back on a development spanning several decades. Starting with the so-called low-temperature superconductors (LTS), today innovative solutions are being advanced by means of high-temperature superconductors (HTS). An essential key in the investigation and qualification for the application and the validation of the modeling of such cable concepts is the conclusive experiment. This is made possible by the so-called FBI facility (F=force, B=magnetic field, I=current). This setup already formed the basis for the characterization of LTS cables at 4.2K more than 20 years ago. Due to the new requirements for HTS cables, regarding test temperature (variable 4.2K to 77K) and permanent high operating currents up to 10KA, it was inevitable to replace essential components of the equipment and to extend the characterization possibilities. After a 2-year modernization phase, during which the complete wiring was also replaced, it is now possible, for example, to observe the dynamic quench process of a cable by means of a multichannel measurement and to compare it with models (Fig. 9). Experiments on different cable architectures based on a CroCo triplet were used to test the measurement and control technique [1]. The facility is now part of the EUROfusion test facilities of the work package magnets (WPMAG).

DETERMINATION OF THERMAL CONTACT RESISTANCES

Quenching experiments in the FBI facility or in the Swiss SULTAN facility demonstrate the limits of safe operating parameters of superconducting cables for magnets. To

Fig. 9: Newly built measurement system of the FBI-facility.

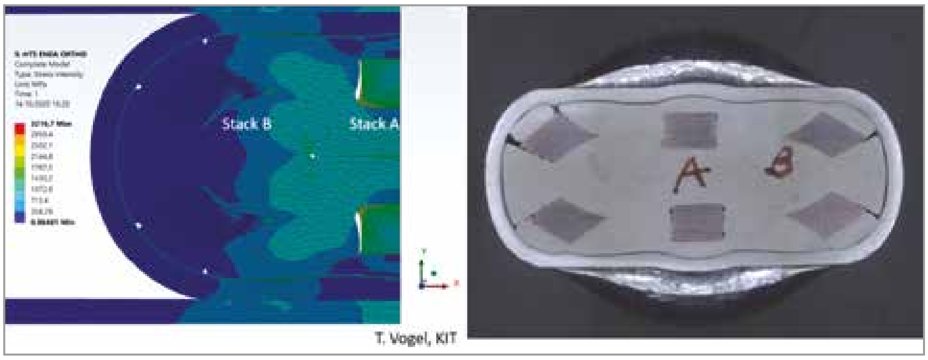

Fig. 11: Comparison of the FEM modeling of the deformation under shear forces with the result of the experiment (original round cable diameter approx. 2.6 cm).

model the behavior of different cable architectures, not only the superconducting properties of the HTS tapes but also the material properties of the normal conducting components used are essential. Therefore, an experiment to determine the heat transfer between copper and steel, respectively, was already designed last year and first results could be obtained [2]. However, the influence of the contact pressure on the heat transfer was already evident. Due to the Lorenz forces acting on the cable in a magnet, this is an essential parameter in the description of the electrical and thermal contact resistances of the cable components. As part of a master's thesis, a special measuring frame was developed to determine the thermal contact resistance under variable contact pressure (Fig. 10). Systematic experiments were carried out between 2K and 300K at variable contact pressure on copper-copper, steel-steel and copper-steel combinations. In addition, the influence of surface roughness and scaling with different specimen dimensions is analyzed in the process. The master thesis will be completed in 2022 with a comprehensive analysis of the results.

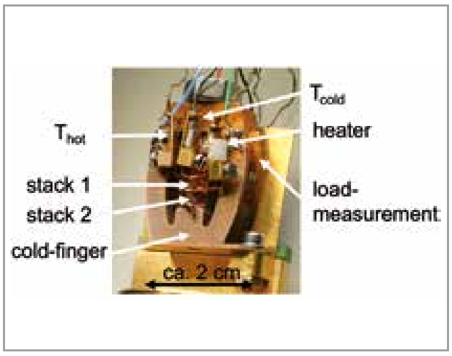

Fig. 10: Instrumented copper frame with two inserted stacks (Cu-Cu) to measure contact pressure simultaneously.

ELECTRO-MECHANICAL MODELING OF SUPERCONDUCTING CABLES.

The relationship between the experimental results at the cable level, the material properties of the components (e.g. steel sheath, copper or aluminum for stabilization) is reproduced by modeling. Using the finite element method (COMSOL), a comprehensive description of a 6-slotted cable in conduit (HTS) provided by ENEA (Italy) has now been accomplished. Mechanically, the deformation of the cable by transverse forces from the conducted experiment [3] is correctly reproduced in this case (Fig. 11). Furthermore, the electrical as well as the thermal behavior is analyzed in such a way that statements can be made about the behavior, for example in the case of a quench. The method will be applied to different HTS cable layouts.

PROJECT ADHYBAU

The national hydrogen strategy of the Federal Republic of Germany includes funding for a wide range of strategically relevant research projects. In the BMWi-funded project Additive Hybrid Construction (AdHyBau), Siemens, MT-Aerospace, Fraunhofer IWM, TU-Dresden are working with ITEP to develop the prototype of a hydrogen-powered, electric aircraft engine. ITEP is performing basic cryogenic material characterizations on lightweight alloys and combined carbon fiber composites. The results of the cryogenic material properties are essential for the engineering work of the innovative design approaches. The first publications on this are scheduled for 2022.

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Contact: Klaus.Weiss@kit.edu

Results from the Research Areas

Test setup of two 20 kA sub-conductors for a 200 kA industry busbar

Energy Applications of Superconductivity

Coordination: Prof. Dr.-Ing. Mathias Noe

In the research field Superconducting Power Applications, ITEP scientists work on the following topics:

- Superconducting network and energy components
- Modeling of superconductors and components
- Real-time system integration

SUPERCONDUCTING NETWORK AND ENERGY COMPONENTS

The focus in the topic of Superconducting Grid and Energy Components is on the development of novel operating materials for electric power systems and the development of resource- and energy-efficient applications for energy technology. To this end, researchers achieved the following results in 2021.

The DEMO200 (Novel Superconducting High Current System for 200 kA Direct Current) joint project, which began in 2019 and is funded by the BMWi, aims to work with partners Vision Electric Superconductors, Messer, Trimet and Theva to develop the technology for a compact and efficient industrial busbar with a current rating of 200,000 A and demonstrate its functionality in a test. This would mean a tenfold increase in current compared to the state of the art of 20 kA and would enable a wide range of applications in industry. Within the project, ITEP has taken on the task of characterizing the superconducting tapes, co-developing the basic geometry and contacts, and performing a test on a scaled busbar element. In 2021, an important project milestone was reached in which two 20 kA subconductors were successfully tested at 77 K with the rated current provided for them. The test was preceded by numerous preliminary investigations into the selection and contacting of the superconductors. Now the construction of the 200 kA technology demonstrator in an industrial environment is targeted for 2022.

As part of the BMWi joint project SuperLink to develop a 110 kV, 500 MVA superconducting cable for the inner city of Munich, a simulation model was set up to calculate the temperature during overcurrents and the subsequent recooling. Figure 2

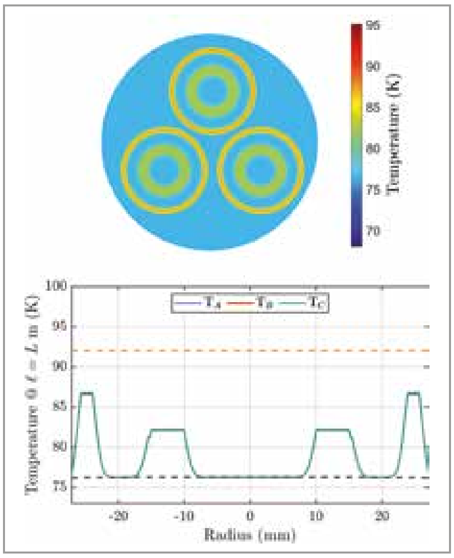


Fig. 2: Temperature curve in the cable cross-section after the occurrence of an overcurrent

shows an example of the temperature development in the cable cross-section. The model was checked with calculations of the industrial partner and very good agreements were found. Thus, three-phase, adjacent superconducting cables can now be modeled very accurately with respect to their electrical and thermal behavior.

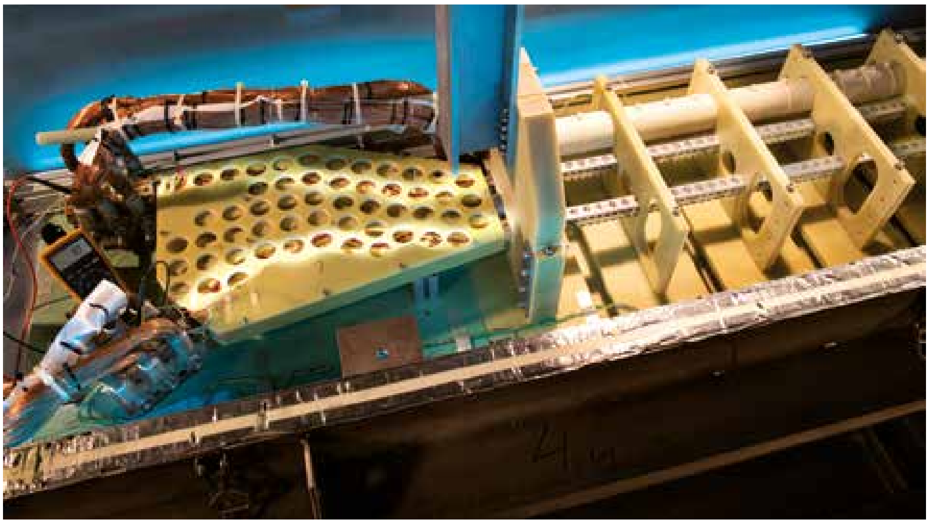


Fig. 1: Connection and construction of the modular subscale test with two superconductive 20 kA subconductors.

Within a cooperation with Rolls-Royce Electric a still unfinished test rig for testing fast rotating cryogenic superconducting coils could be delivered to our institute. Within a newly started PhD thesis on the development of superconducting 3D coils for rotating machines, this test rig will be completed and put into operation in the next years.

In 2021, several studies for the applications of superconducting lines and current limiters for different power companies could be processed. In particular, the increase in short-circuit power as a result of the grid expansion caused by the energy turn-

Fig. 4: RIS bushing (left) and in build in condition (right) with Schering bridge measurement.

around, causes the need and demand for superconducting current limiters to increase significantly. Furthermore, the technical and economic feasibility of a GW DC transmission line at a voltage of only 50 to 100 kV was investigated and compared with conventional solutions.

Superconducting magnetic heaters enable energy savings of more than 30 percentage points over previous methods when heating metals for industrial use and have already been built and operated in single units. However, not all operational requirements have been met to date. The main objective of ITEP in the BMWi joint project ROWAMAG (Robust and low-maintenance magnetic heater with high-temperature superconductor coils for hot forming processes) to build and test a robust and low-maintenance magnetic heater with superconductors is therefore to develop a long-life cryosystem including the cryostat and the refrigeration equipment. Together with the partners, Theva, Bültmann and Maschinenfabrik Beck, the superconducting coil was integrated into the housing (Fig. 3) in 2021. All components have been manufactured and the assembly of the superconducting magnet has started at ITEP. Furthermore, the cryocoolers to be used have been extensively pretested in 2021.

High voltage bushings for cryogenic applications are preferably solid insulated to avoid problems of condensation or sublimation of gaseous insulating materials. In the medium-voltage range, glass-fiber-reinforced plastics were used, among other materials, for small series at ITEP. For the medium and high voltage range, commercially manufactured insulators based on epoxy resin impregnated paper (RIP) windings have been used so far. For conventional high-voltage bushings, other materials have been used for a few years in very humid conditions because degradation of the insulation associated with humidity occurred with RIP technology. Therefore, a new type of RIS (resin impregnated synthetic) insulation wrap was investigated in the cryogenic high voltage laboratory. For cost reasons, an AC bushing with a rated voltage of 25 kV was selected. In the type procured, the insulation is located directly on a central copper rod. The rated current of the bushing is 2 kA. Due to the solid copper inner conductor with no gas barrier to the surrounding insulation, icing was to be expected on the room temperature side surface. An outdoor bushing was therefore procured.

After 5 thermal cycles with cooling times from room temperature to 77 K of about 2 hours, no damage was observed. In addition to the verification of suitability as an AC bushing, high-voltage tests for DC bushings were also successfully completed. All high-voltage tests were thus passed. Two defects were found during the leakage test. One defect on the pressure relief screw on the retaining flange does not require further investigation because this device will not be needed in future bushings. The axial leakage from the vessel chamber to the room temperature side head end must be prevented in the future by better sealing.

Fig. 3: Superconducting coil casing

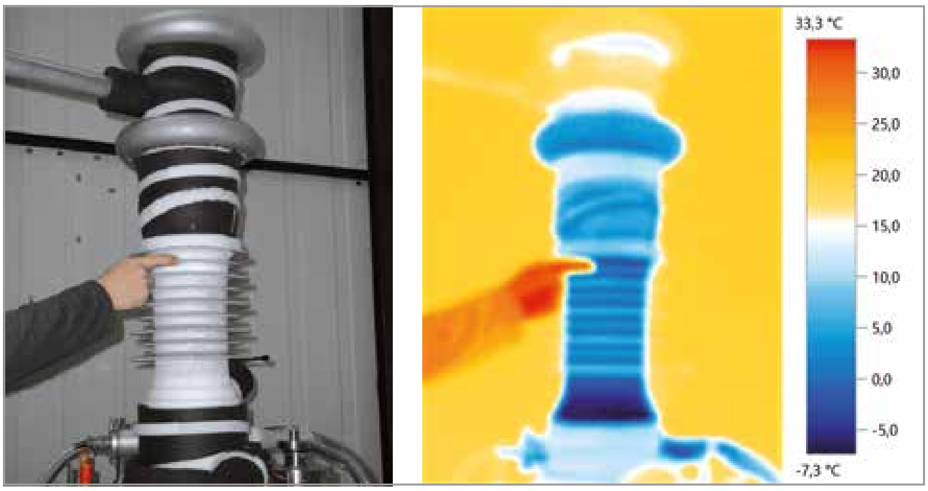


Fig. 5: RIS bushing in optical (left) and thermography picture (right). The lowest temperature is at -7,3 °C.

Thermal insulation was provided only with insulation material for indoor use. This measure proved to be sufficient to prevent ice formation in the area of the voltage connection at the room temperature side end. The temperature measurement on the cooled test specimen (Fig. 5) shows the sufficient effect of the thermal insulation at the upper end for the operation carried out indoors. It can also be seen that no ice formed on the ribs. For continuous operation, improvements of the thermal insulation in the area of the lower flange mounting would be useful to reduce the losses.

contact: mathias.noe@kit.edu

MODELLING OF SUPERCONDUCTORS AND COMPONENTS

In order to study the potential of a fully superconducting generators, an in-house model was developed to design a fully superconducting wind generators which has no stator iron teeth or rotor iron poles. There are two challenges in the design of these type of generator: (a) the determinations of the operating currents in the stator and rotor coils, the operating relative permeability of stator and rotor cores are dependent on each other due to nonlinear relation to magnetic field; and (b) the complexity of the AC loss estimation of the stator coils due to the combined effects of AC magnetic field and supplied AC current. To tackle these challenges, an iteration process based on analytical equations was developed for the determinations of operating current and relative permeability and for the updates of geometry parameters. Figure 6 shows the graphical user interface of the developed algorithm. Then the determined operating current and relative permeability can be used as the input parameters for estimating the AC loss in the stator by means of finite element software.

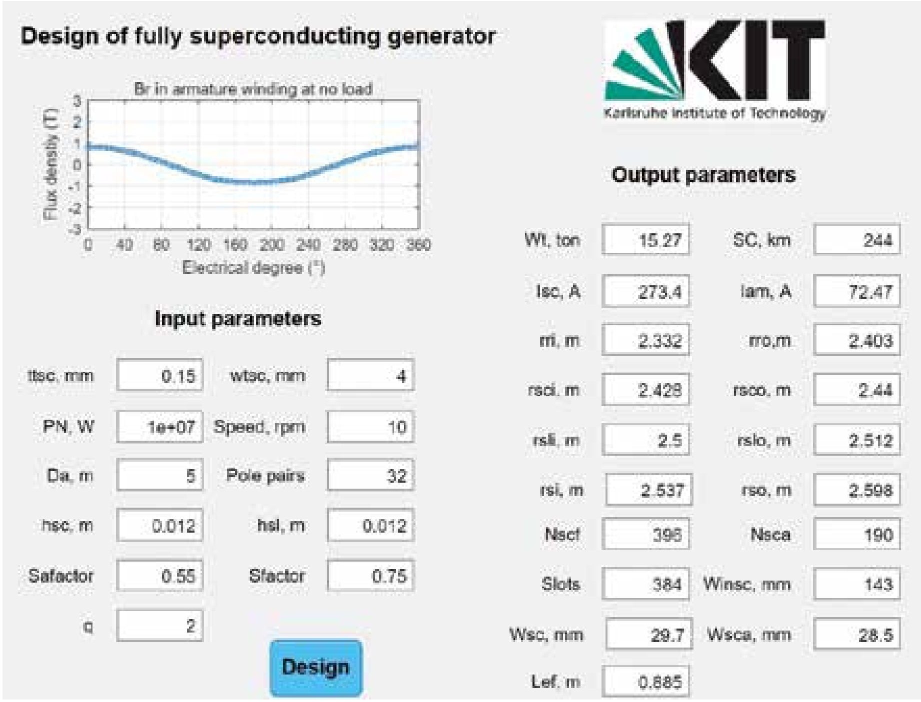


Fig. 6. Graphical user interface of the developed tool for designing a fully superconducting wind generator.

Within the BMWi project SupraGenSys, finite-element method simulations based on the T-A formulation were used to study several configurations of the stator coils in order to try to minimize the losses of a 10 MW superconducting generator for wind turbine applications. The best arrangement is based on non-planar coils and reaches an 85% reduction in AC losses in comparison with the classical racetrack coils. This new configuration allows better usage of the superconducting tape capacity by achieving a more uniform current penetration in tapes and avoiding saturation of individual coils. The findings encourage the development of inclined coils and more complex configurations to face the technical challenges of superconducting generators for wind turbine applications.
The T-A formulation was extended to three-dimensions in order to enable the calculation of AC losses in superconducting coils with complex shapes. For this kind of calculations, the superconducting turns are not simulated individually, because this would generate a too large number of degrees of freedom, resulting in unpractical problem sizes and computation times. Instead, the superconducting turns are homogenized into a unique conductor, which allows the use of a much less detailed mesh. Fig. 7 shows the comparison of the current density distributions obtained by simulating all the individual turns and with the homogenized technique: the results are practically indistinguishable, but the homogenized problem can be solved several time faster. The model has also ben validated against experiments from the literature, and then used to investigate the electromagnetic behavior of coils with more complex shapes, such as racetrack coils (including the end effects), D-shaped coils and twisted stacks of HTS tapes for fusion applications.

In order to introduce students to some important topics relevant for superconduct-

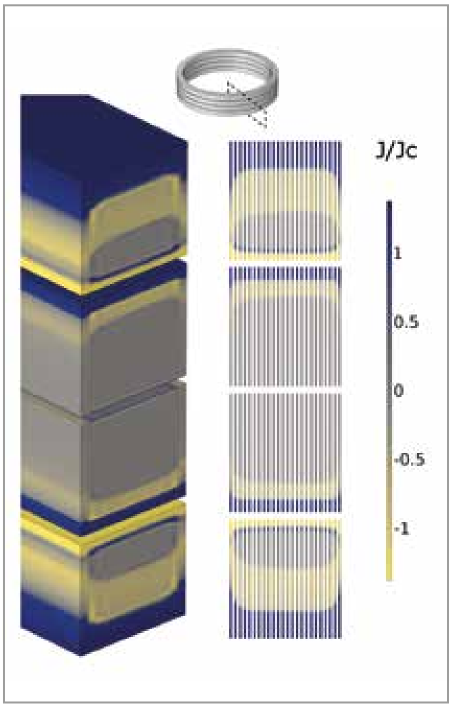


Fig. 7. comparison of the current density distribution in four HTS pancake coils, calculated with the homogenized and non-homogenized models.

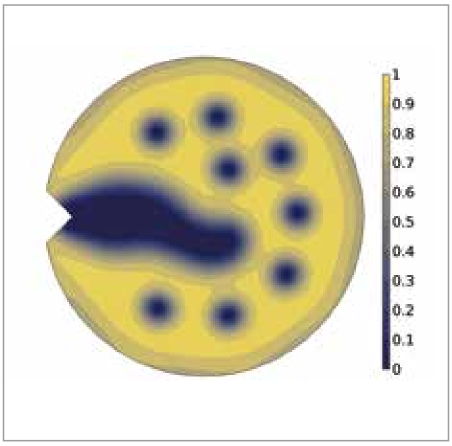


Fig. 8. Example of magnetic flux penetration in a type-II superconductor calculated with the numerical models available on the applications web server AURORA (https://aurora.epfl.ch)

ing applications, a web server of applications based on COMSOL Multiphysics has been launched in partnership with Ecole Polytechnique Federale de Lausanne. With these online applications, student can focus on the relevant aspect of physics and can run the simulations from everywhere: the only thing needed is an internet connection. At the moment, there are seven applications ranging from physics of superconductors (Fig. 8) to large scale applications.

Contact: Francesco.Grilli@kit.edu

REAL-TIME SYSTEM INTEGRATION

The Real Time System Integration group deals with the modelling, control and experimental validation of high-power energy technologies. Our focus lies particularly in developing new efficient real time models of these energy technologies, that are experimentally validated, and can reproduce the hardware behaviour with the highest details accuracy.

In July 2021, the Helmholtz Young Investigator Group "Hybrid Networks: a multi-modal design for the future energy system" started its activities. The focus of this young investigator group is on the design of multi-modal and power electronics-based energy systems (Fig. 9). The research topics include the development of methods for efficiently reducing the computational time of energy resources modelling in digital real time simulators, without impacting on the model accuracy; the development of new control solutions for asynchronously-based grids, that help to increase the controllability of the whole energy system; the proposal of new approaches to tackle the short-circuit problem in power electronics-based grids; the development of new experimental test bench, the multi-modal hardware in the loop, that will enable to perform multi-modal validation of energy technologies in realistic conditions.

At the beginning of 2021, the 60kW 3.6kWh high-speed flywheel of the company Stornetic has been validated extensively with the power hardware in the loop approach. The flywheel has been modelled in a digital real time simulator, and the model accuracy has been validated by means of experimental results. Realistic test cases have been considered, such as the large UK frequency deviation in 2019. As can be seen in Fig. 10, where the simulated model has been compared with the hardware performance under the same frequency input, there is only mini-

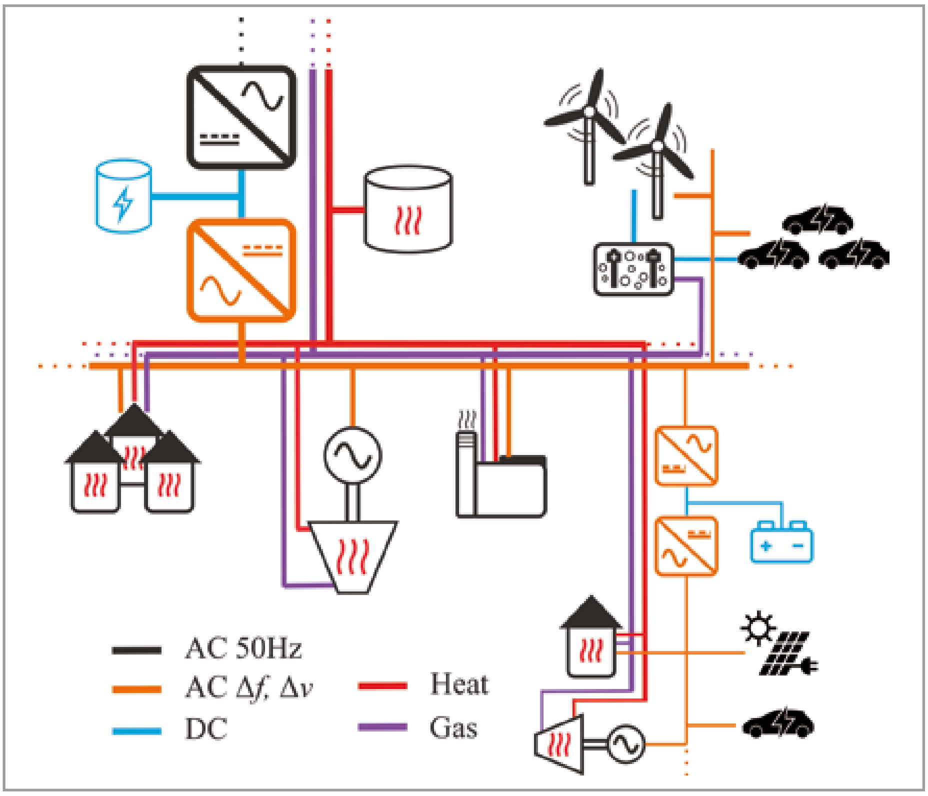


Fig. 9: Hybrid Networks concept

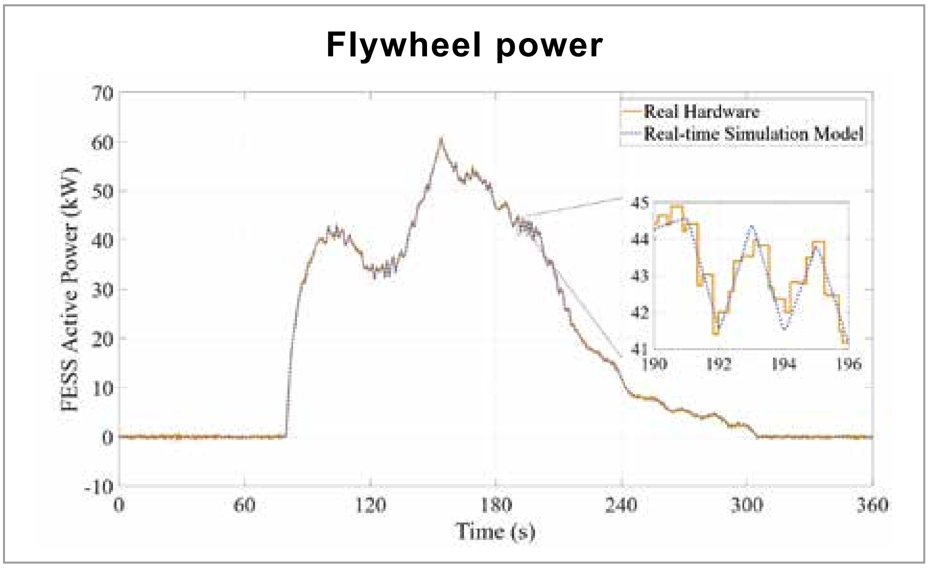


Fig. 10: Flywheel power profile of real hardware (yellow line) and simulated model (blue line).

mal mismatch between them. This prove the model accuracy for frequency control in realistic grid conditions, and the results have been published in an international journal.

Additional advancement has been performed also in the modelling of multi-modal resources, such as the 3.5 kW electrical and 15kW thermal micro-gas turbine present in Energy Lab 2.0.

As first step, in the BMBF-Verbundprojekt Sektorkopplung (SEKO), the micro-gas turbine (Fig. 11a) has been modelled in both Simulink and own script code, validating the performance of the script code in term of accuracy (<1% error) and computational time gain (29x reduction of simulation time). Additionally, the models have been compared against the hardware results under different modelling assumptions (in Fig. 11b, the output electrical power has been plotted), showing a good match between the simulated and the experimental results. Additional investigations are planned for the 2022, considering also thermal and gas variables in the modelling.

The year 2021 has been characterized also by the strengthening of the collaboration between the Real Time System Integration group and the particle accelerator KARA at campus north. The Future Fields Stage 2 project "Energy solutions for large-scale infrastructures for research and society: from component to system level" has been awarded to investigate the energy saving potential solutions in particle accelerators. In order to achieve this goal, a communication infrastructure between KARA and Energy Lab 2.0 has been designed and is currently under construction that allows to transfer the electric variable data (e.g., voltage and current) in real time (e.g., at 10kHz rate) in the digital real time simulator present in Energy Lab 2.0. This communication infrastructure allows to develop data-driven models of the accelerator KARA in real time, and thus to validate the performance of energy technologies (e.g., the 60kW flywheel) by means of the power hardware in the loop technique. The project is on-going and it will be finalized during the next year.

In the superconducting area, progresses in the modelling of superconducing cables have been made. The 2D finite element model of a HTS cable has been realized for transients purpose within the Super-

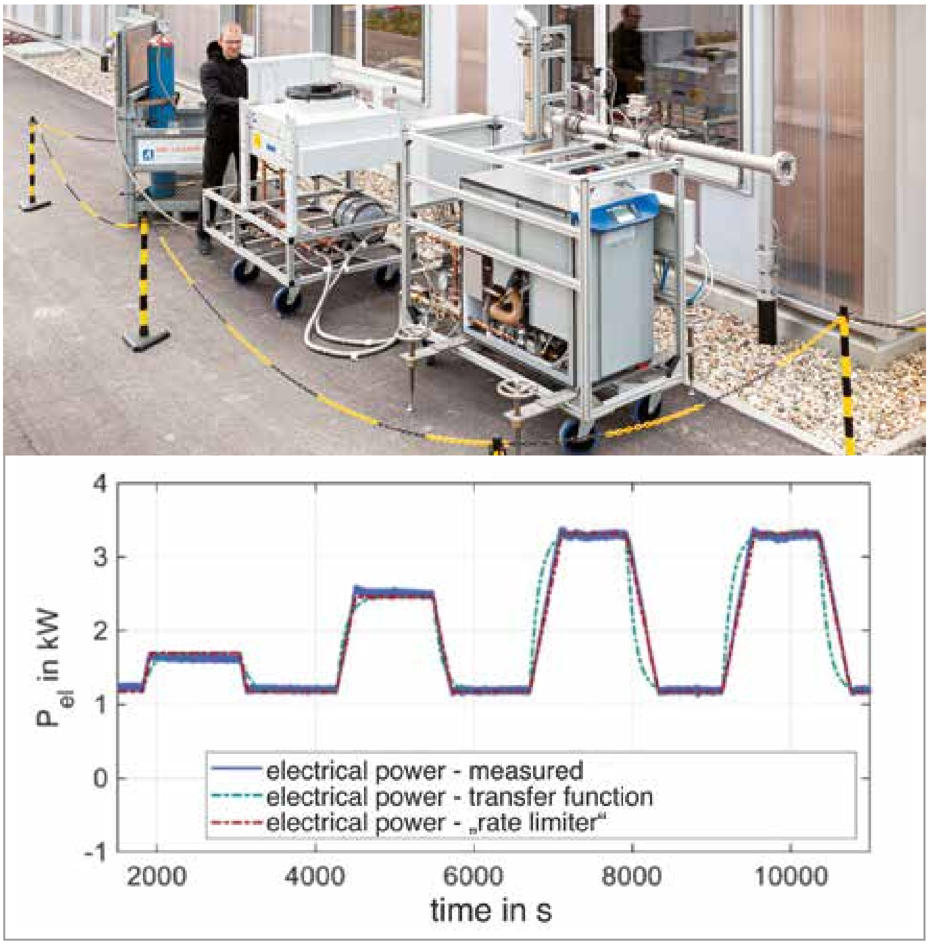


Fig. 11 Micro-gas turbine (a) setup, (b) experimental validation of the developed models – electrical power in kW.

Link project (Fig. 12), and then used as base for the development of a model for real time digital simulation, showing accurate performance for the targeted applications.

The Power Hardware In the Loop (PHIL) Lab has made great improvements with respect to the previous year, starting officially operations in 2021. The PHIL Hall has been divided in 5 functional areas, that are fenced and can operate independently from each other. This feature increases enormously the testing possibility of the PHIL Hall, because it allows to run up to 5 different experiments in parallel. Large equipment have been purchased, in order to extend the simulation and experimental capability of the lab: OPAL-RT licences (FPGA, RT-Lab, ePhasorSim), RTDS licences, a 45kW Spitzenberger&Spies linear power amplifier, a 250kW DC emulator, and software to improve the controllability of the 1MVA Egston power amplifier group. The flywheel system will be expanded to 120 kW as well. In addition, two new test facilities are currently being designed and implemented.

Within the BMWi joint project Flygrid, a 500kW, 1.6kWh supercapacitor energy storage system will be installed in and will operate for the first time at the beginning of 2022. This storage system, acting as fast power source can provide fast dynamic services to the grid. Furthermore, in Energy Lab 2.0, the supercapacitor system will enable its combined use with the flywheel, in order to assess the performance of hybrid energy storage systems in providing services, such as voltage and frequency support to the grid, in realistic grid conditions.

Currently, a 50kW liquid hydrogen power plant is under design in Energy Lab 2.0. ITEP and IAI are joining effort to build an electrolyser, liquefier, tank, fuel cell hydrogen storage system, that connected to the PHIL setup, will allow a realistic assessment of the hydrogen potential in the future energy system. The final design and the beginning of the construction works is planned by the Q2 of 2022.

Contact: giovanni.carne@kit.edu

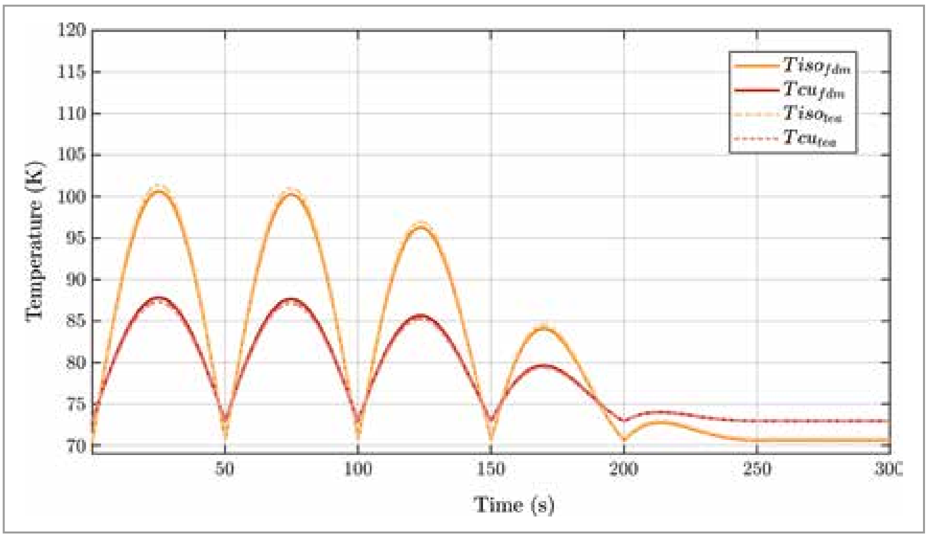


Fig. 12 Finite Element modelling of HTS cable, and its validated real time model.

Results from the Research Areas

Robotic winding of a simple pancake coil. A 2-axis positioning robot supports the winding body. The winding hand is located on the interchangeable tool of one of the two 6-axis robots. Here a steel band represents the HTS for process qualification.

Superconducting Magnet Technology

Coordination: Prof. Dr. Tabea Arndt

In 2021, the restructuring of the research group that had been planned in 2020, covering both structure (research topics) and content, was implemented. The research area of superconducting magnet technology is now divided into the following research fields:

- Coil and magnet technology
- High current components for hydrogen technology and fusion
- Rotating machines

The research field of coil and magnet technology is now equipped to develop novel techniques for superconductor wires and their windings, which can also take on complex, non-planar shapes. As a result, HTS wires in particular can be used advantageously in various applications and complex geometries.

The research field high-current components for hydrogen technologies and fusion continues the development of HTS high-current conductors and applicable experiments. The second focus on hydrogen technologies significantly increased its importance in 2021. The joint project AppLHy!, funded by the BMBF, started in 2021 and is coordinated by ITEP. AppLHy! is part of the TransHyDE technology platform, one of the three lead projects of the BMBF for the "Hydrogen Republic of Germany" within the framework of the National Hydrogen Strategy (https://www.wasserstoff-leitprojekte.de/).

The research field rotating machines brings to an end the work on wind power generators and is now specially dynamic due to the possibility of using so-called DUDA coils in rotating machines. This coil technology is particularly advantageous for compact machines or machines with high power density (wind power, vehicles).

COIL AND MAGNET TECHNOLOGY

The realignment and broader direction of the research field "Coil and Magnet Technology", which began in 2020, continued steadily during 2021. The work focuses on the development of innovative technologies for the production and operation of superconducting coils and magnets for specific applications. In addition to conceptual work, the current focus is on robotic winding technology, functional vacuum-pressure impregnation and the development of alternative cooling concepts using cryo-coolers and thermo-syphons. The provision of space and infrastructure for the new test facilities is happening alongside the renovation of the laboratories and the dismantling of obsolete old facilities.

ROBOTIC WINDING

The increasing demand for coils with complex, real three-dimensional geometries, which are no longer easily wound by hand, requires innovative winding devices. A robotic facility was designed for this purpose, consisting of two non-collaborative industrial robots and a rotatable, pivoting component positioner. The two robots wind the superconductor while the component positioner holds and orients the coil body. A so-called "winding hand" guides the superconductor and is docked via flanges on rotating feeds that are located on the last axes of the robots. In order to be able to wind complex geometries that require reaching around and through, two robots are required that transfer the winding hand to each other in order to alternate.

The construction of the system was completed during the reporting period (Figure 1). In detail, this meant the designing of a control cabinet with the necessary system electronics, building the control electronics for the robots and completing the system cabling along with the protective housing. The electronics are connected to the robot controller and programmed and certified according to the safety require-

Fig. 1: Facility for robotic coil winding with component positioner (left) and the two robots. The right hand robot carries the winding hand with the supply coil.

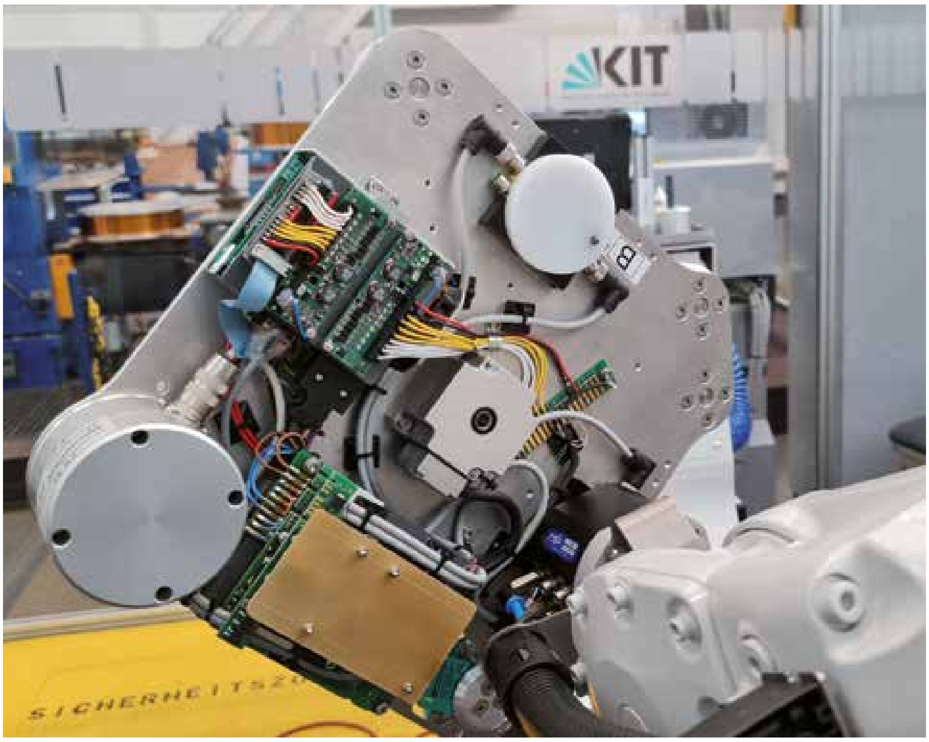


Fig. 2: Winding hand docked on one of the robots. The electronics side with servomotor (middle) and tensile force sensor (left) are visible.

ments. The RobotStudio control software, which simulates winding processes using a digital twin of the robot system, was also installed on a PC and programmed after successful validation.

The main achievement was the construction and commissioning of the in-house designed wrapping hand. The disc-shaped winding hand guides the wire and maintains the winding tension during the winding process. To achieve this, the supply reel is mounted on the shaft of a servomotor and the tensile force during the winding is measured directly via a gravity-compensated tensile force sensor. Possible external influences on the tensile stress - e.g. by transferring the winding hand from one robot to the other - are compensated for in real time using a specifically programmed PID control. A rotary encoder measures the length of the conductor used (Figure 2).

Once the system for robotic winding was completed, the first disc-shaped pancake winding was built during the reported period. One of the robots circled the spool, which was fixed on the component positioner, and wound the wire in layers (Figure 3).

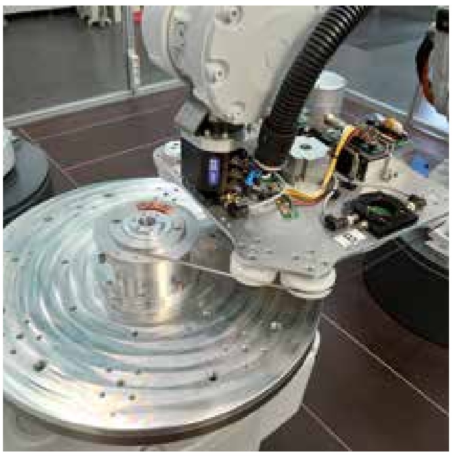


Fig. 3 Winding of the first disc-shaped pancake coil.

VACUUM PRESSURE IMPREGNATION

ITEP prepared all the necessary operating documentation for the VPI system procured in 2020. In 2021 the team carried out the first tests for developing an impregnation technique for coils that are wound with HTS tapes. This was achieved by building and impregnating dummy pancake coils made with steel tape. In the experiments, focus was on the casting and hardening behaviour of various impregnation materials with and without additives, as well as the choice of suitable, many times reusable, impregnation moulds. The vacuum chamber of the facility allows for coils up to a largest dimension of approximately 1 m.

COOLING CONCEPT: THERMOSYPHON WITH CRYO-COOLER

The use of HTS in energy technical applications takes place typically in the temperature range between liquid helium (4.2 K) and liquid nitrogen (77 K). Dry cooling by cryo-coolers can be used to achieve this. The coupling of the cold head of the cooler to the object to be cooled is usually carried out by heat conduction via a solid copper material. Much greater heat transfer is attained by innovative thermos-syphons, in which a small amount of a thermos-syphon-enclosed cryogen transfers energy by means of substance transport and phase transitions. The copper evaporator and capacitor are connected to the object to be cooled, or the cold head. The cryogen (here e.g. neon) evaporates on the object to be cooled, flows over a pipe to the capacitor, where it liquefies and flows back to the evaporator. The construction of the thermo-syphon demonstration system (already designed) started during the reporting period, and the control panel for the piping was built (Figure 4).

In addition, the workshops at KIT constructed and manufactured all mechanical components. Therefore, in the coming

Fig. 4: Initial construction of the thermos-syphon test rig. Left: Cryostat input with cold head and thermo-syphon. Right: Control panel of the equipment's pipework.

year, the construction of the system will be completed and commissioning will take place.

RECONSTRUCTION WORK

With the successful commissioning of the expansion stage of the high-field experiment system Homer II (which now provides magnetic fields up to 26.5 T in a cold bore of 68 mm in diameter with an HTS insert magnet), the predecessor facility, Homer I, was technically superseded and therefore superfluous. At the same time, there is a need for a cryogen-free test environment for larger current-loaded superconducting components without background field, cooled by cryo-coolers. ITEP procured components of a corresponding test system with cryostat and cooling device at short notice and to provide space and infrastructure for this facility, the Homer I apparatus was completely dismantled. The cryostat of the new test facility is built in the hole of the Homer I cryostat. The Homer I cryostat will be used for liquid hydrogen storage in the Energy Lab 2.0 of KIT.

Contact: frank.hornung@kit.edu

HIGH CURRENT COMPONENTS FOR HYDROGEN AND FUSION

QUENCH ANALYSIS IN HTS FUSION CONDUCTORS

The work already started in the past two years to investigate quench behaviour in high-temperature superconducting cables for use in future fusion magnets continued as part of an international cooperation. The goal of the project is the experimental test of the quench behaviour of such a sample in fusion-relevant conditions in the superconducting test facility (SULTAN) in Switzerland. In particular, the proposed conductor arrangement was tested in the FBI facility at KIT. Figure 5 shows the schematic cross section of the cable as well as a photograph of a front of the sample built and tested in the FBI facility.

When constructing the sample tested in the FBI facility, all relevant steps (which are also required by the approximately three times as long sultan sample) were tested separately and checked by successive individual measurements of the superconductors after each production step. The production sequence consists of the production of the three superconducting HTS CroCo conductors, the soldering of these conductors into copper profiles, the twisting of the three conductors, and the attachment of the electrical connections and the capsules of the conductor into a longitudinal welded steel housing. Figure 6 shows the results of the measurements of the critical current of the sample. For each production step, no degradation of the conductor occurred. The increase in critical

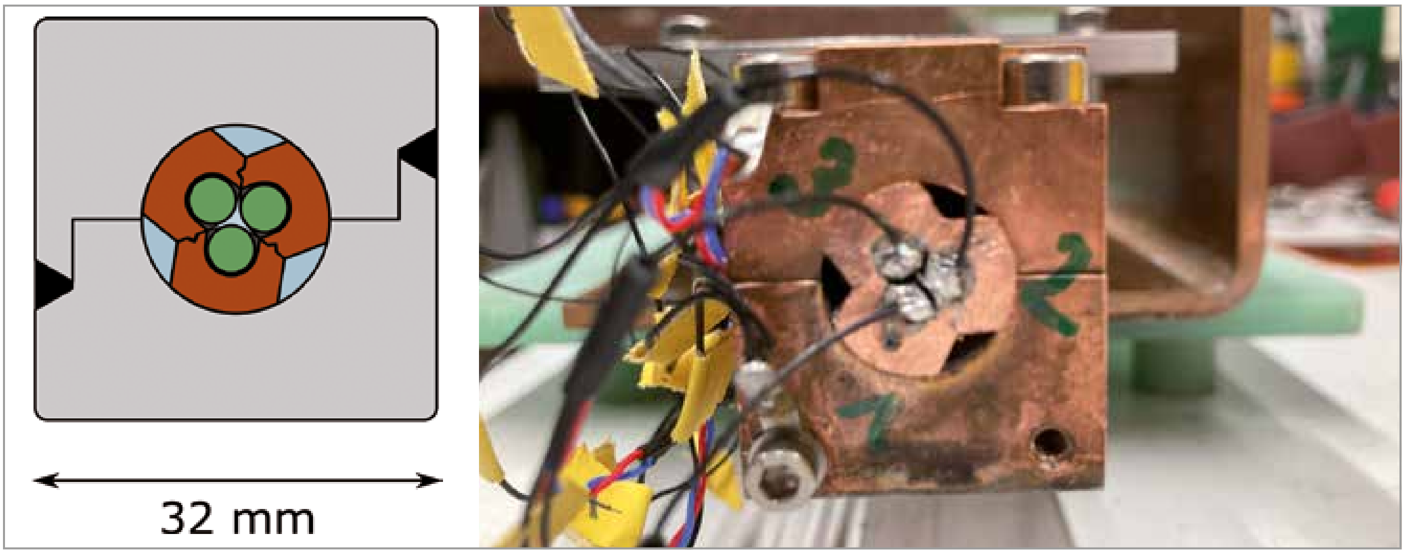


Fig.5: Schematic cross section of the triplet-conductor and a photograph of a front end of the finished probe, tested in the FBI facility.

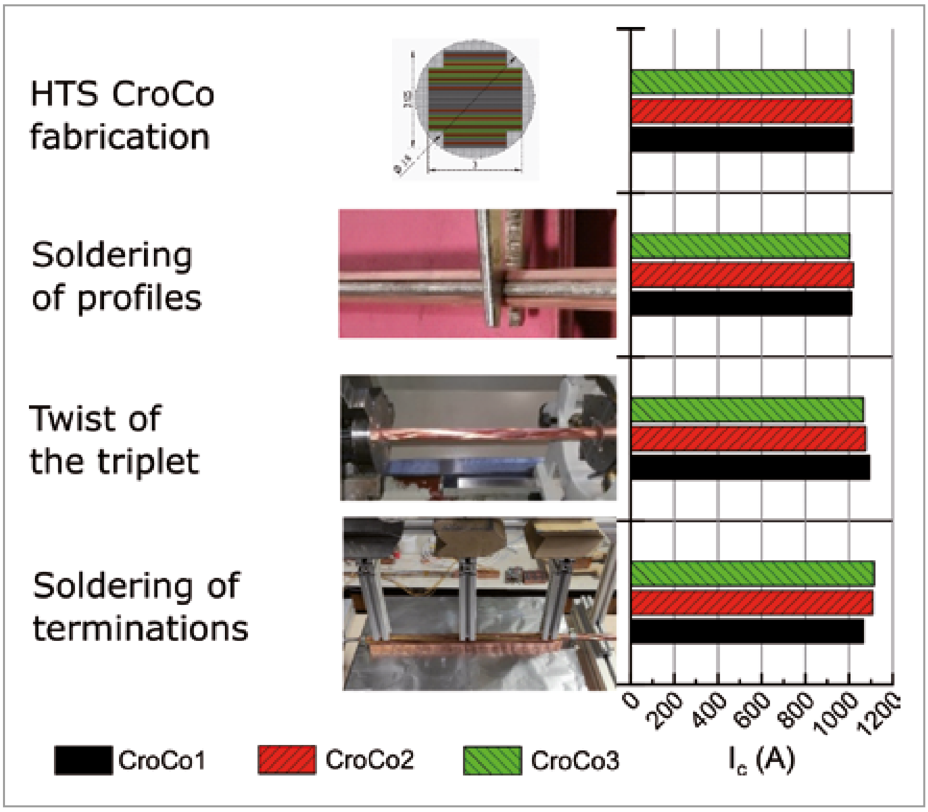


Fig. 6: Qualification of the production stages by measurement of the critical current of the three HTS CroCo conductors of the triplet at T=77 K.

current during the construction stages can be explained by the adding to and enlarging of the copper cross section at each step.

After the successful qualification steps, a test was carried out in the FBI facility at T = 4.2 K and magnetic fields up to 12 T. The aim of the test strategy was to check the sample design when subject to high Lorentz forces resulting from the currents and fields. Various instrumentation concepts and arrangements were also investigated.

Figure 7 shows a sample after the final pre-test and the magnetic field dependency of the critical currents of the three individual conductors.

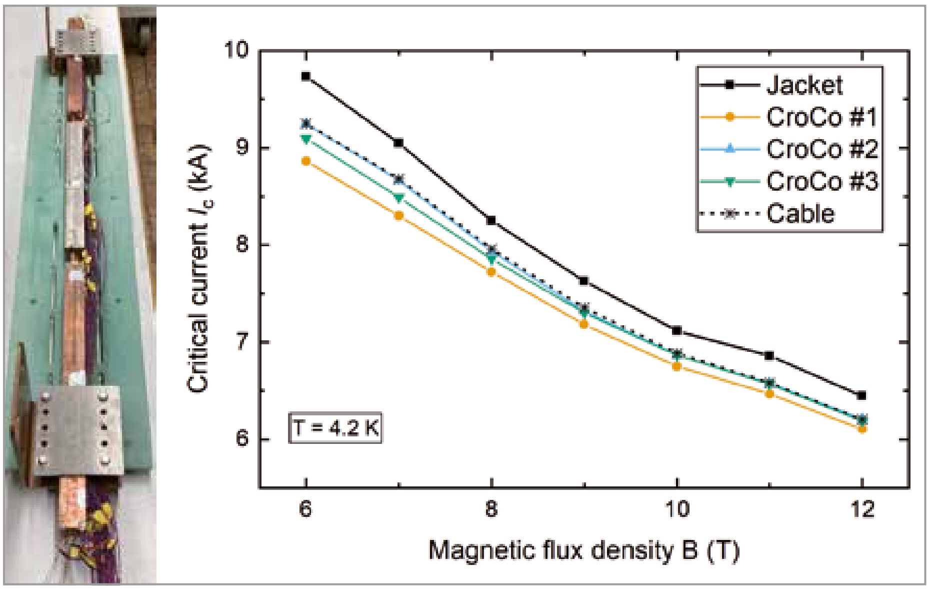


Fig. 7: Triplet sample during the final pre-test in LN2 and the magnetic field dependence of the critical currents of the three HTS CroCos at T = 4.2 K.

Based on the successful pre-tests and test strategy in the FBI system, the production and assembly of the sample for the test in the Sultan system began and some milestones, such as the production and characterization of the superconducting HTS CroCo conductor, were successfully completed. The completion of the sample is therefore expected in early 2022.

Contact: michael.wolf@kit.edu

HIGH CURRENT COMPONENTS FOR HYDROGEN

In 2021, KIT received the grant notification for the joint project AppLHy!, funded by the BMBF. A focused ITEP team was then able to successfully combine the project proposal from 12 individual partners into one of the three (namely TransHyDE) lead projects for the National Hydrogen Strategy / for the "Hydrogen Republic of Germany".

Figure 8 shows the simple logo of the joint project AppLHy! The project, with a total budget of > € 15 million and an initial term of four years, researches the transport and use of liquid hydrogen (LH_2).

In order for the CO_2-free energy vector hydrogen in the form LH_2 to achieve suitable penetration of energy systems, significant developments and applications are necessary. The following themes are thus addressed, together with our partners:

Fig.8: Logo of the joint project AppLHy!.

- Efficient liquefaction and transport (container)
- Safety and materials
- Concepts for LH_2-driven electrical equipment in energy technology
- Secondary use of low-temperature cooling and the hybrid energy transport by means of a pipeline for LH_2 and electrical energy – the latter conducted by means of HTS cables.

It should be emphasized that, within the project, not only research but also implementation work (in particular a test platform for the hybrid energy transmission pipeline) is being carried out. Therefore, there is also intensive cooperation with the other research areas and the cryo-technology of ITEP as well as with other institutes of KIT (ETI, IAM-WK, ITES).

Liquid hydrogen not only offers a high level of purity and energy density, but also a temperature level for the direct use of HTS in electrical equipment (motors, generators, cables, transformers, etc.) without additional cooling costs. Therefore, HTS couples electrical engineering with hydrogen technology creating further efficiency and performance advantages.

This synergy is also evident in the contributions of the other research topics: The new systems for coil and magnet technology, the work on the cables for fusion technology and the design of the rotating machines are all valuable additional work. This work cannot be achieved solely with the available resources and teams, which is why we are working – despite the difficult conditions in the pandemic – on a corresponding increase in personnel so that this new strategic focus can progress satisfactorily. If necessary, the current work can continue in follow-up projects (two three-year notification periods).

Contact: michael.Wolf@kit.edu, tabea.Arndt@kit.edu

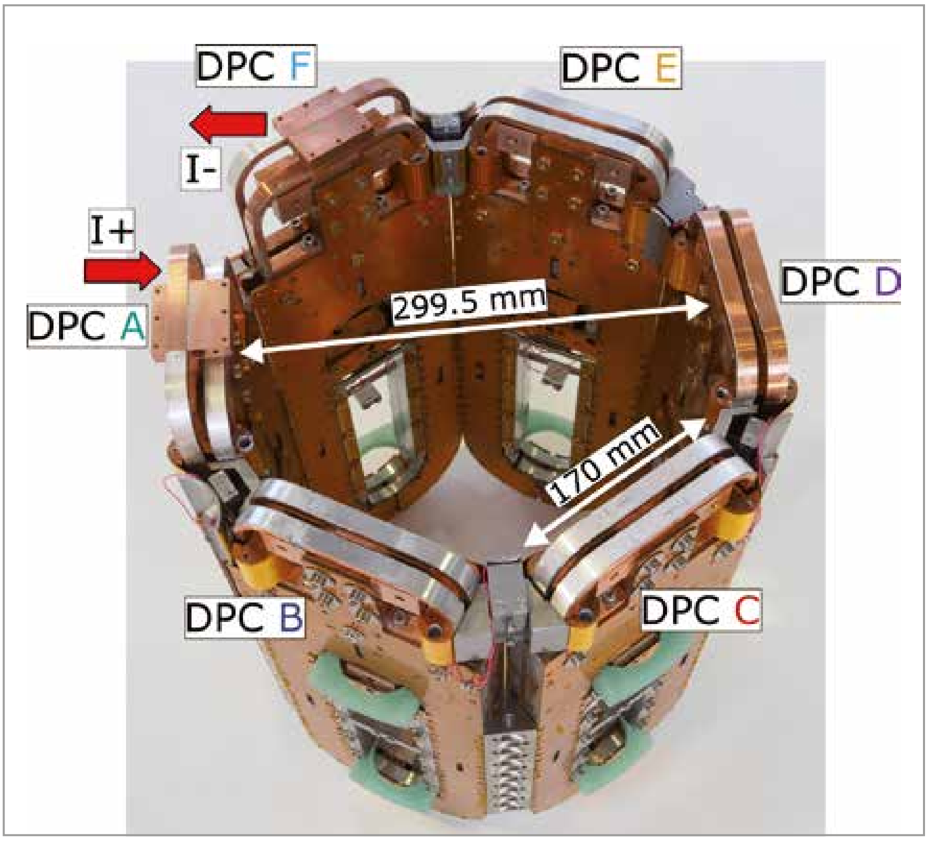


Fig. 9: Six-pole superconducting coil system.

ROTATING MACHINES

SUPERCONDUCTING GENERATORS FOR WIND TURBINES

The power density in directly driven wind turbines can be more than doubled compared with conventional permanent magnet generators by the use of superconducting field coils. These compact and light machines offer considerable savings potential in terms of transport and the installation of wind turbines of higher performance classes. Therefore, the ITEP is working on the design and construction of a generator with superconducting field coils as a technology demonstrator. The six-pole coil system (Figure 9) consisting of 12 individual pancake coils was successfully tested in liquid nitrogen at a temperature of 77 K. To increase thermal and electrical stability, the pancake coils do not have electrical insulation between the coil windings.

The superconducting coil system was then integrated into the entire generator system in order to carry out tests at temperatures below 77 K. Cooling is achieved by a cryogen-free, line-cooled, two-stage cooling system. The superconducting coil system reached a critical current of almost 700 A at a minimum temperature of 30 K and thus fulfils the requirement for an operating current of 450 A. Furthermore, the required alternating pole formation at the corresponding field strength can be determined from the magnetic flux density measured in the centre of the coils (Figure 10). Additional measurements of the charging and discharging behaviour, as well as a continuous current supply, demonstrated the basic functionality of the system.

TEST STAND FOR HTS-ROTORS

Within the framework of a strategic development investment by HGF, the HTS-Geno Test Rig project was approved for 2021 and subsequent years. The aim of the project is to set up a test stand for the development of coil technology and cooling of large superconducting motors and turbo generators. The HTS coils are cooled to 30 Kelvin with the help of a neon-filled thermo-syphon circuit. The operating current of the superconducting coils is up to 3 kA and the coils rotate at a speed of up to 3000 revolutions per minute. In 2021, the team evaluated the construction drawings and information from a preliminary project. The cryo-coolers were ordered and work on the infrastructure began. The track system, which has to support the entire 40-tonne structure, consisting of carriage, vacuum container, shaft with motor and cryogenics, is under construction. The construction of the vacuum container is almost complete (see Figure 11) and will be commissioned in 2022. For a more flexible use of the test rig, the team is currently investigating design changes to the rotor barrel on which the superconducting coil is mounted.

ROTATING MACHINES WITH DUDA-WINDINGS

The round disk-up-down arrangement (DUDA), originally developed for miniaturized magnet coils, consisting of levels of structured 2G HTS, has been developed to include rectangular arrangements [1]. In conventional, normally conducting motors, the greatest power densities are produced in synchronous machines with field excitations from rare earth permanent magnets (PM). If the rotors are replaced by coils wound with 2G HTS tapes, the

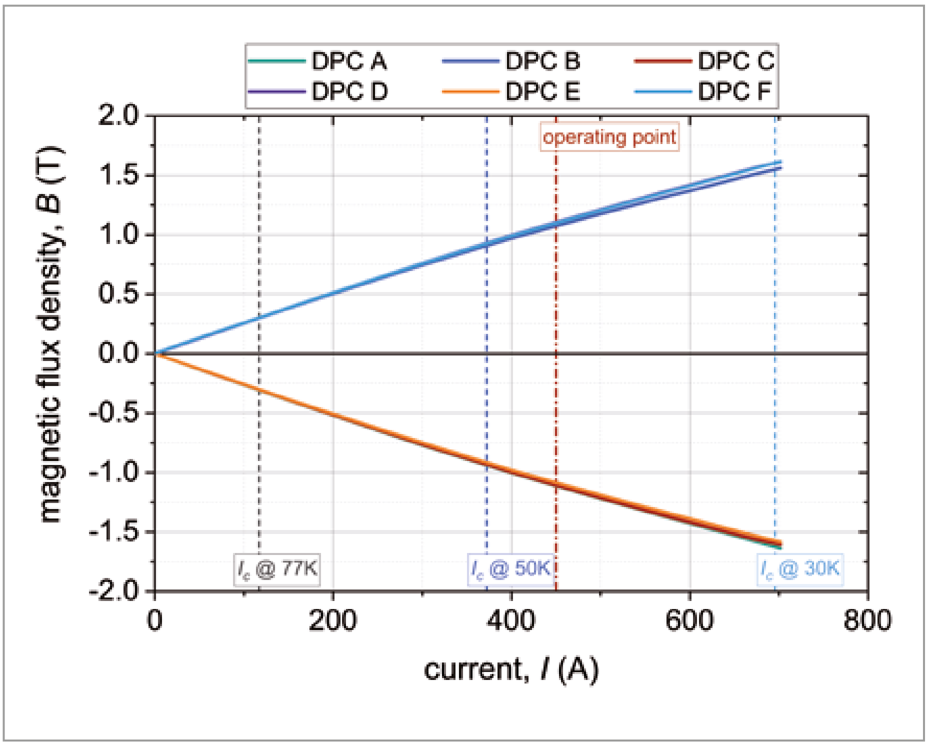


Fig. 10: Dependency of the magnetic flux density measured in the coil centre on the excitation current.

power density can be increased further. However, the minimum requirements for the radii of curvature of the tapes and the winding heads themselves limit the number of poles, i.e. the number of poles of 2G HTS rotors is not as high as that of PM

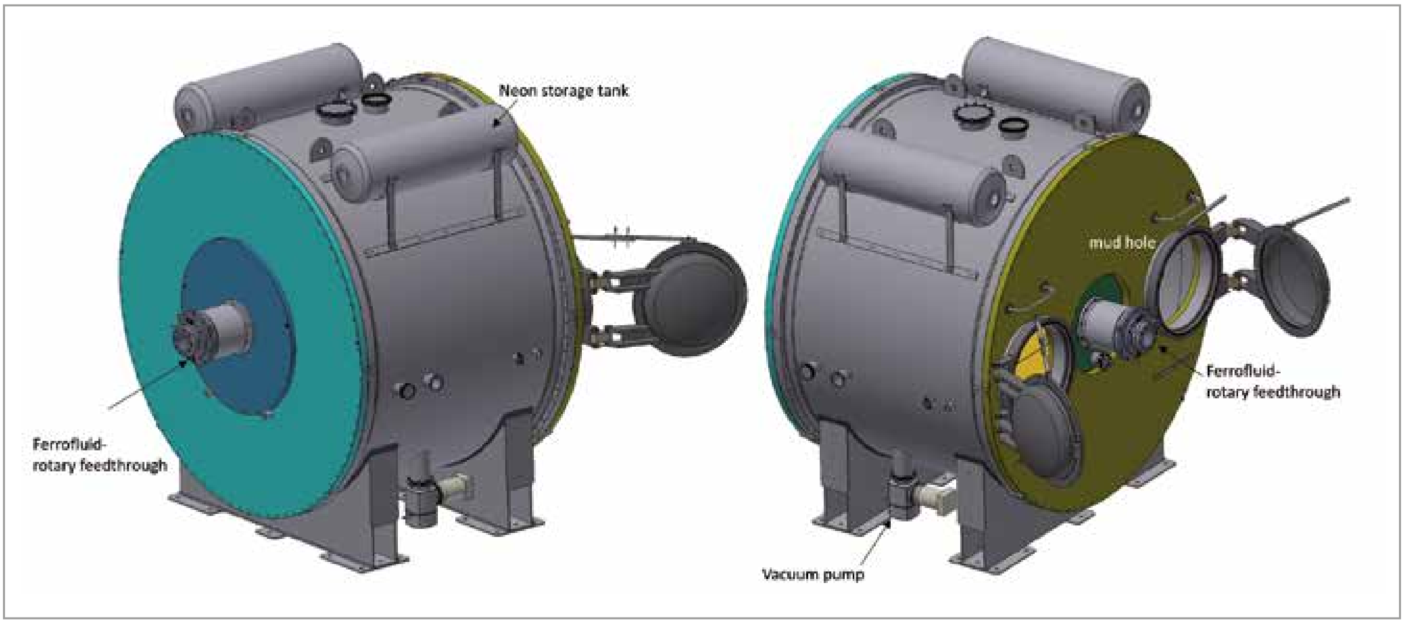


Fig. 11: Vacuum container of the HTS-Geno test rig, diameter 3,15 m, length 2,25 m, weight c. 16,2 t.

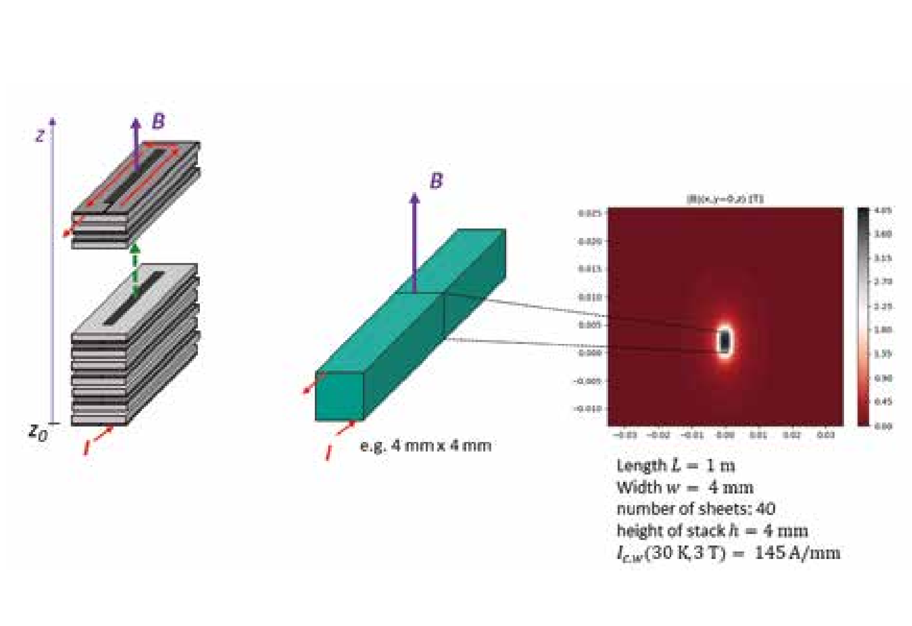
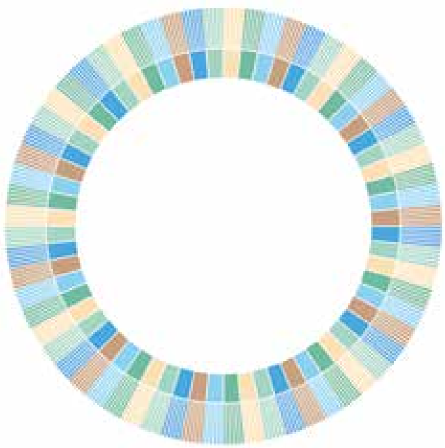


Fig. 12: Schematic diagram of a compact, rectangular DUDA coil for rotating machines.
Left: stack structure, middle: stack as a component, right: magnetic fields in the defined plane.

[1] Arndt, T., et al. (2021). "New coil configurations with 2G-HTS and benefits for applications." Superconductor Science and Technology 34(9).

Contact: tabea.arndt@kit.edu

rotors (rotors with conventional rare earth permanent magnets). This applies to both large wind power generators and compact drive motors. Since the number of slots in the stator is effectively linked to the number of poles in the rotor, the machines with "classic" wound coils are limited. However, if suitable DUDA coils (Figure 12) replace the conventional permanent magnets, the poles can be miniaturized and significantly larger numbers of poles can be achieved. In addition, this drastically reduces the space requirement for the winding heads. Since the achievable air-gap magnetic field for such 2G-HTS DUDA coils exceeds the saturation field strength of iron teeth, in the stator a so-called air-gap, or more precisely air teeth winding, is used, which has only an iron yoke arranged behind the stator coils. An analytical approximation model was developed for such a high-pole air ratio machine, to enable quick, rough electromagnetic designs of these machines. Figure 13 shows such an approximate design of a DUDA vehicle machine, which - at a temperature of approx. 20 K (liquid hydrogen) – has an excellent power density. Follow up work will continue this approach.



Parameter	Value	Unit
Leistung	7,3	MW
Speed	3000	rpm
Length	0,300	m
Air-gap radius	0,200	m
Number of pole pairs	32	n.a.
Excitation current (at ≈ 20 K)	400	A
Number of notches	384	n.a.
Air gap radius	0,2	m

Fig. 13: Schematic cross-section of the coil arrangement in a DUDA-vehicle motor for operation at c. 20 K (liquid hydrogen).

Highlight
Robotic Winding of programmed Trajectories

The commissioning of the robotic facility for winding coils with HTS represents a significant milestone in construction technology.

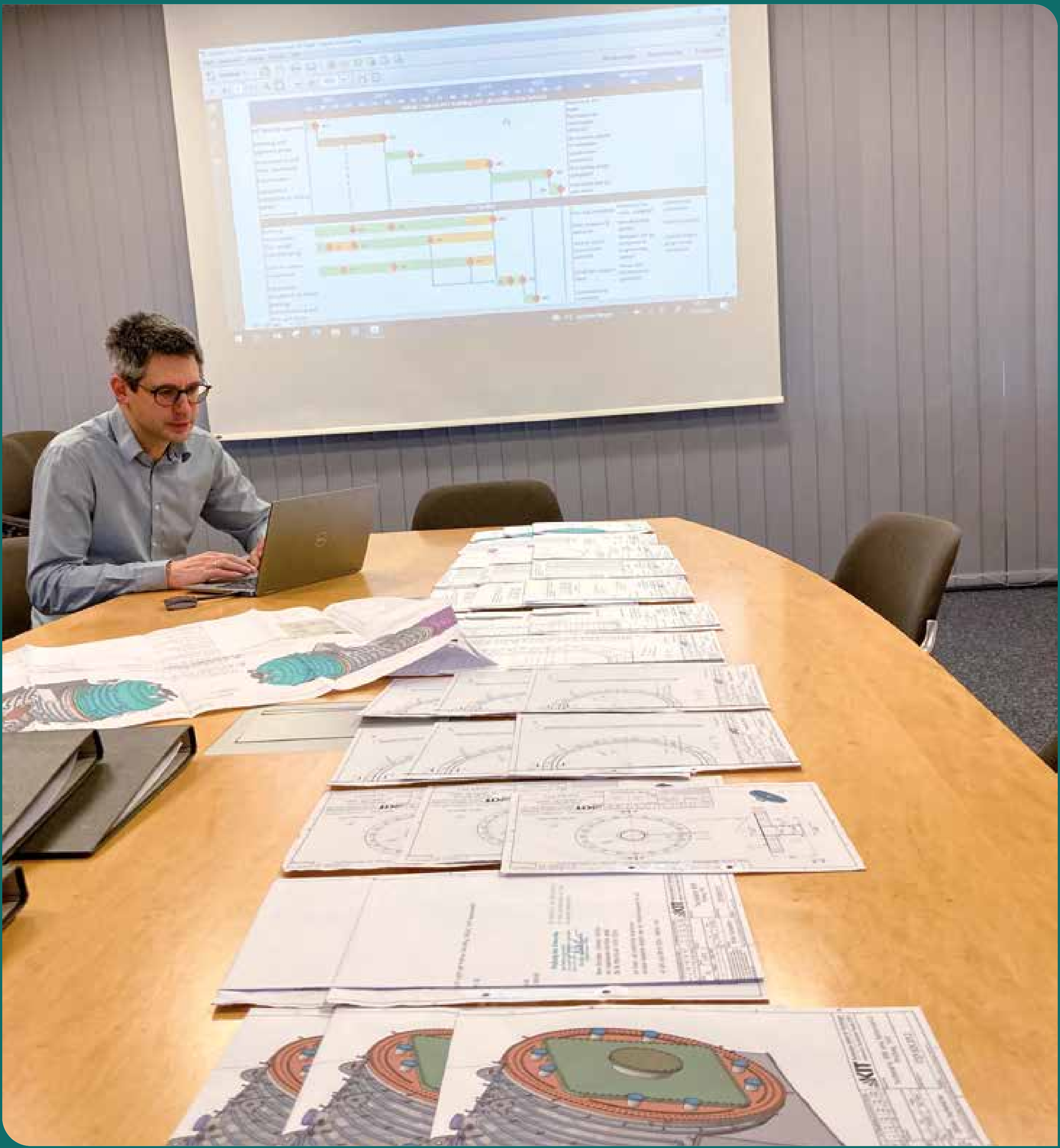
Fig. 14: Preparation of the first coil by means of the digital twin and the actual hardware.

In the preliminary tests, the winding process was verified in advance using the digital twin on the PC (RobotStudio). This meant that the winding shape was combined with the 3D image of the robot in the software by importing the design data. The desired trajectory (3D spatial coordinates) of the wire was subsequently parameterised mathematically in the robot's movement commands.

Since robots generally strive to maintain a large range of motion to minimize the twisting on the individual axes, more is required than just entering the target coordinate of the wrapping hand. In the course of the winding process, this would lead to a sudden twisting of the robot arm with a corresponding twisting of the winding wire. This is acceptable and even desirable for pick-and-place, welding, painting or gluing robots so that the supply cables and tubes are only slightly twisted along the arm. In the case of superconductor wires, this would lead to degradation or tearing. Therefore, to avoid such a "minimization strategy", the various permitted movement ranges of the axes of the robot must be defined in addition to the spatial coordinates of the wrapping hand (in so-called quaternions, which are not very clear but are mathematically defined). Furthermore, the dynamic movement parameters (speeds and accelerations) permitted must be adapted so that the winding process runs smoothly and gently, and is compatible with the internal controls of the winding hand. This encompassed the fundamental groundwork. A particular advantage of this robotic winding technology is that not only circular coils or pure racetrack coils (consisting of two semicircles and two straight sections) can be wound in the plane, but also that any Lamé ovals can be realized by simply changing the mathematical description of the trajectory. These planar coil shapes have the advantage that a radial tension is always maintained during the winding process, which ensures that there is no “slack” in the winding.

These developments are the basis for the subsequent winding work on non-planar (3D) coils in 2022 and their application in, for example, in the stators of rotating machines, as well in concentrated windings, and even more so in spread out windings. These coils require further mathematical description and programming care, which will be addressed in the near future. In addition, this technology makes possible the preparation of HTS coils for the acceleration magnets (starting with dipoles with simple saddle coil geometries). This robotic winding technology does not require the manufacture of a suitable winding machine for every application and coil shape but can perform a wide variety of tasks. This technology is also a helpful tool for other research topics (high-current components for hydrogen and rotating machines).

Results from the Research Areas



Auf zu neuen Ufern – DIPAK geht los.

Technologies for the Fusion Fuel Cycle

Coordination: Dr.-Ing. Christian Day

In the research field "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 utilized. The research field covers all three key fuel cycle technologies: matter injection, vacuum technology, and tritium technology.

The following current research topics have emerged in the research field:

- Vacuum technology and process integration,
- Rarefied gas dynamics,
- Vacuum hydraulics and hydrogen separation.

The work is firmly linked to the European Fusion Programme **EUROfusion,** which will develop a concept design of the demonstration fusion power plant DEMO by 2027.

2021 was still very much characterized by the constraints imposed by the Corona pandemic. Nevertheless, as every year, we achieved extremely impressive results. This is due to the extraordinary commitment of the whole team. We are very proud of this.

VACUUM TECHNOLOGY AND PROCESS INTEGRATION

The research topic "Vacuum Technology and Process Integration" addresses all vacuum-related questions around a fusion plant and develops an integrative approach for their description with the help of a fuel cycle simulator for DEMO. The work also covers vacuum technologies for other large-scale fusion facilities, such as the European neutron source IFMIF-DONES or the fusion devices currently under construction: JT-60SA in Japan and DTT in Italy.

ITEP's Vacuum Technology Division has been working for many years with the team at the **JT-60SA** tokamak in Japan, which will be commissioned in 2022.

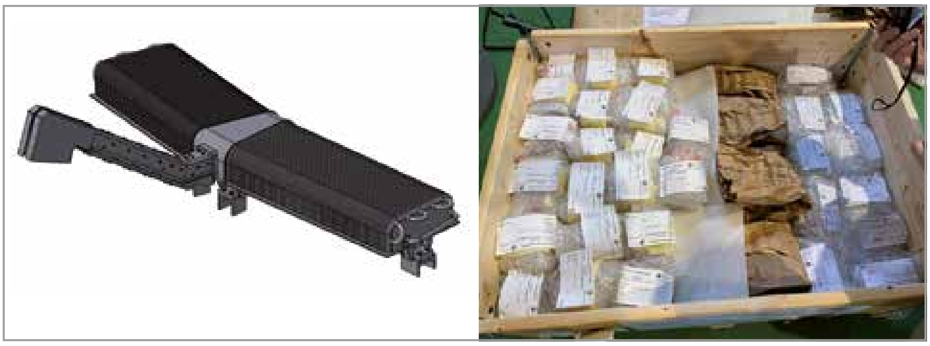


Fig. 1: Design of the cryopump for JT-60SA (left). First components in production (right).

After an initial experimental campaign, the machine will be reopened in 2023 and completed with further installations. This includes a powerful cryopumping system (nine identical cryopumps), which will be integrated directly into the divertor. The ITEP was commissioned to develop the complete design for this, to accompany the production in the industry and to ensure the quality-compliant execution.

Figure 1 (top) shows the final design of the cryopump. It follows the proven cryosorption pump concept developed at the Institute: the thermal shield is shown in the figure. The cryosurfaces are modularly constructed from hydroformed panels, two per pump wing. The first parts (Figure 1 right) have already been manufactured and delivered to Japan.

To finalise the manufacturing design, a large number of design changes had to be incorporated. In particular, the complex welds proved to be a special challenge for the manufacturer.

For the IFMIF-DONES material test facility, which is being built in Granada/Spain, the Institute´s Vacuum Technology Division is charged with integrated vacuum modelling. DONES is an accelerator that generates a fusion-typical neutron spectrum at a liquid lithium target, which can be used to test materials for applications in fusion.

In 2021, extensive modelling of argon gas injection towards the target (at a distance of 90 m from the source) was carried out. The build-up of a total pressure of at least 10-4 mbar is required to suppress vaporisation of the lithium at the free-flowing surface. The simulations showed that an injection gas flow of $5 \cdot 10^{-3}$ mbar l/s is necessary for the intended pumping system along the beam path with turbomolecular pumps, cryopumps, NEG and sputter ion pumps to meet the requirements. Figure 2 shows the partial pressure profile that occurs. Between 90 m and about 60 m, argon defines the total pressure; closer to the source, the argon component is masked by the gas load from the outgassing.

Another vacuum technology used at various points in the fuel cycle is based on getter materials **(NEG).** The leading com-

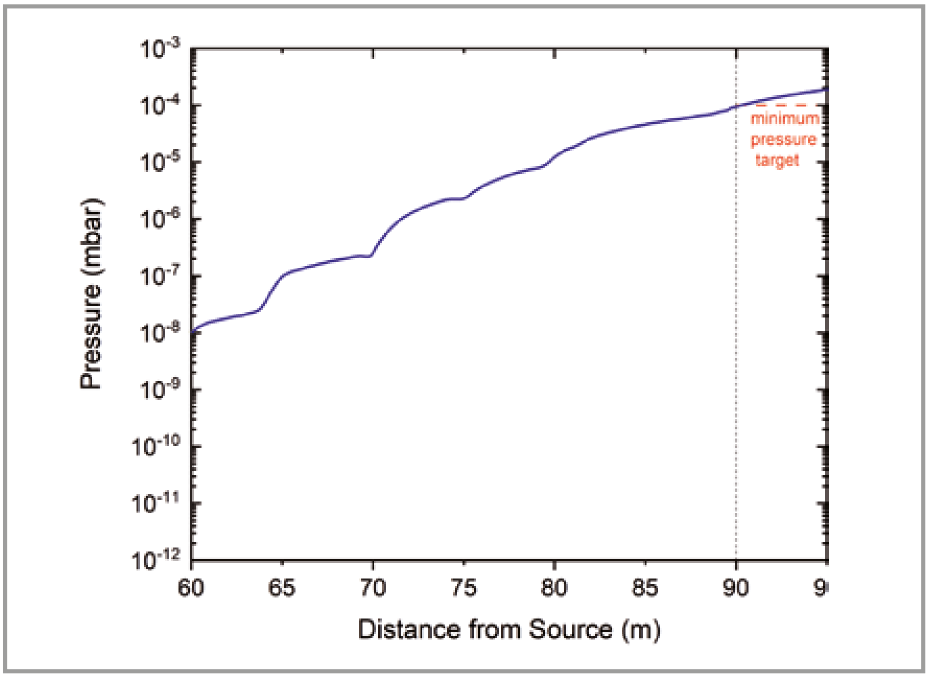


Fig. 2: Pressure profile towards the liquid lithium target at the IFMIF-DONES accelerator.

pany 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. Based on this, a test pump with more than 4600 individual discs was built in 2020, installed in the TIMO test facility, and measured in detail in 2021, see Figure 3.

Based on the measurement results, the pumping speed of the large pump could then be calculated back to the pumping

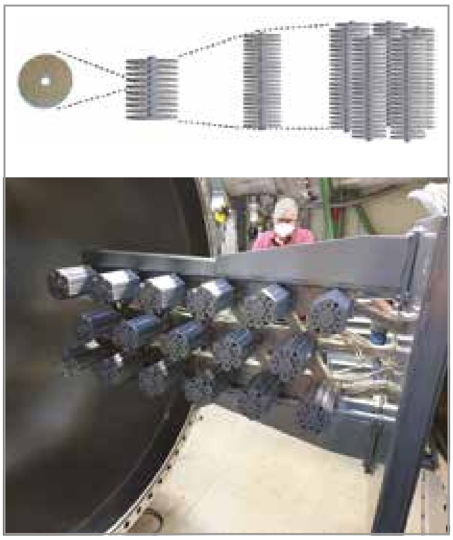


Fig. 3: From small to large: NEG disc (25 mm diameter) (top left), NEG cartridge with 270 discs (top right), NEG test pump when installed in TIMO (with 4590 discs) (bottom).

speed of the individual disc using Monte Carlo simulations. This means that the design of a very large pump (in the order of 1 million disks) can now be developed in the next few years, as it is needed for neutral beam injection in fusion.

Another focus of our 2021 work was the development of DTT's vacuum systems, a new fusion machine in Italy. **DTT** is to develop and demonstrate DEMO's divertor solution; operation is without tritium. For pumping the DTT divertor, two possible solutions have been identified based on NEG pumps with commercial cartridges (cf Figure 3) or on custom-made cryogenic pumps. Both solutions can meet the pumping requirements, but cryopumps provide the highest values in terms of effective pumping speed. In addition, the investment costs for a cryopumping system are much lower, and cryopumping offers a great advantage in pumping the noble gases, as NEG pumps require an additional system to pump these gases. Next year, the proposed pumping solution will be further detailed and adapted to the existing infrastructure. The design of the DTT vacuum pumps will be a focus of work in the Institute´s Vacuum Technology Division over several years.

We have also developed a concept design for pumping the divertor of the SPARC to-

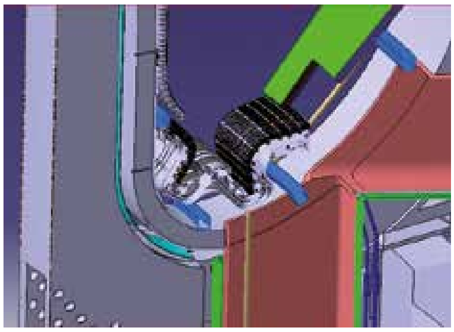


Fig. 4: The DTT divertor with the potential connection channels (red) for housing the vacuum systems.

kamak currently under construction in the USA. Behind **SPARC** is a private company (Commonwealth Fusion Systems) that is developing an alternative path to the fusion power plant. It is based on very high magnetic fields and the consistent use of high-temperature superconductors, which can potentially lead to a very compact design. Accordingly, we were able to find, together with industry, a vacuum solution based essentially on commercially available cryopumps, which, however, have to be converted to be tritium-proof.

For the systematic investigation of thermal gas release rates of materials in vacuum at the test facility OMA (Outgassing Measurement Apparatus), we started with the measurement of simple mild steels. These are relevant for fusion, but also in particular for the design of the third-generation gravitational wave detector newly planned in Europe, the **Einstein Telescope (ET).** ET uses laser interferometers, in whose 10 km long beam pipes a total pressure of 10^{-10} mbar must be achieved for the desired sensitivity. The Einstein Telescope will be one of the largest ultra-high vacuum systems in the world. At such size scales, stainless steel, which is commonly used as a wall material because of its good outgassing behaviour, is not an option for cost reasons.

First results of the investigations in OMA for untreated, chromium-plated and air-heated steel S235JR are shown in Figure 5 in comparison to stainless steel 304 and 316L. For the untreated steel (after an in-situ bake-out), only slightly higher gas release rates were found than for the stainless steels, whereas the chromium-plated

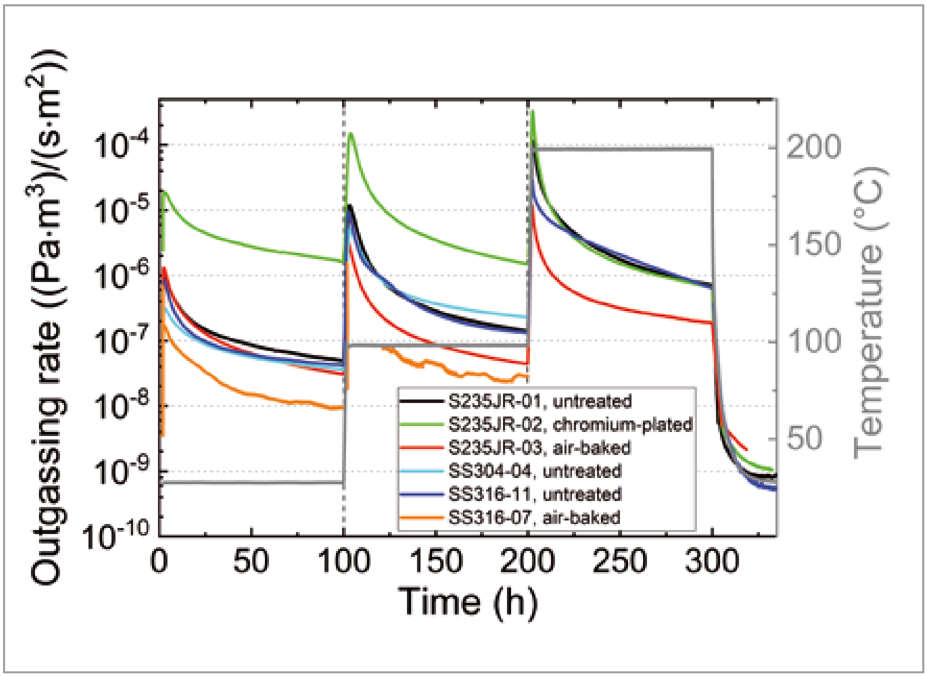


Fig. 5: Measured outgassing rates of steel S235JR, compared with stainless steel.

sample performed significantly worse. By previously annealing the steel sample at 400 °C for 130 h in air, the outgassing rate could be reduced by a factor of 1.5 after 100 h at room temperature. These initial results are very promising.

An initial transfer to the dimensions of ET and the estimation of the minimum pumping speed required showed that further pre-treatments of the steel will probably be necessary and/or the currently planned pumping concept will have to be reconsidered. For this purpose, further investigations of steel with different pre-treatments (such as vacuum baking) as well as other relevant materials for ET will be carried out on OMA in the future, and methods for the reduction, in particular also of the partial outgassing rates of water and hydrocarbons, will be developed.

Contact: christian.day@kit.edu

RAREFIED GAS DYNAMICS

For the correct design of complex vacuum systems such as in the fusion fuel cycle, it is essential to quantitatively calculate rarefied gas flows. The accurate way to do this is by solving the Boltzmann equation, which describes the flow in the entire range of rarefaction. However, the solution of this equation for realistic boundary conditions (complex geometries, gas mixtures) is extremely complex. The ITEP's Vacuum Technology Division is pursuing two different approaches to this: on the one hand, with the DSMC algorithm, which uses stochastic methods, and on the other hand, with deterministic methods (DVM), which solve the equation directly.

In 2021, a major breakthrough in code acceleration was achieved. For this purpose, the code that was previously parallelised on CPU processors (MPI technology) was alternatively parallelised by using graphics cards (GPU technology). For demonstration, the case of particle transport in the DEMO divertor with parametrically varied pumping probability was calculated as a benchmark; Figure 6 shows the underlying geometry and the pressure distribution that occurs.

Figure 7 shows the acceleration compared to the non-parallelised process in a direct comparison of the computing time, namely that 1 GPU unit (NVIDIA V100, 32 GB memory, 7.8 TFLOPS) has the same effect as about 100 parallel CPUs (2 x 24 core Intel Xeon 8160 CPU (Skylake) 2.10 GHz). This means that comparable computing times can be realised on both parallelisation concepts, but the hardware requirements are two orders of magnitude smaller for GPUs. For the duration of the

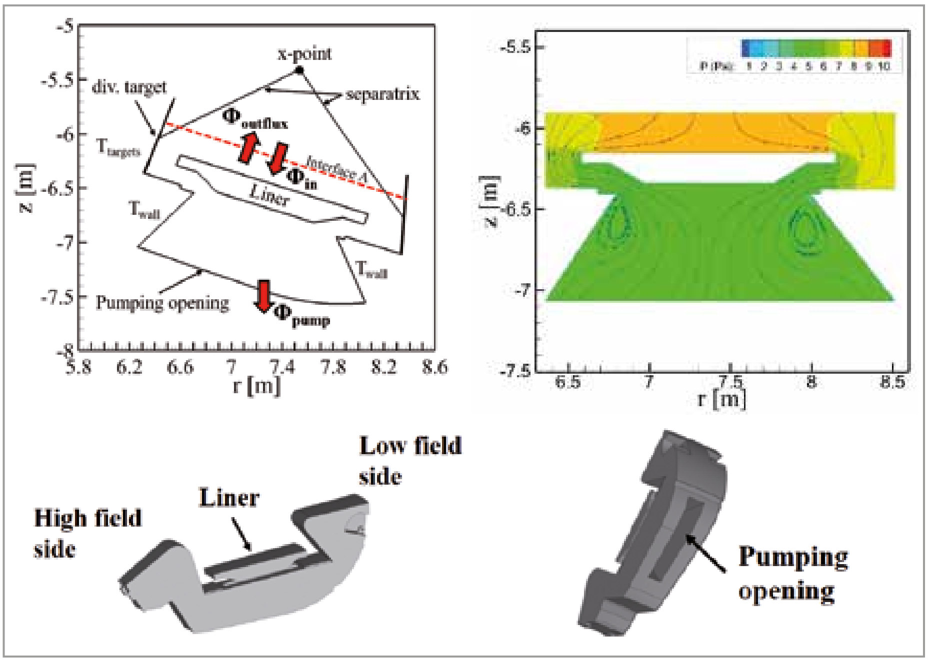


Fig. 6: Benchmark case for the comparison of parallelisation (pumping probability assumed to be 0.1, pressure at the system boundary (dashed red) 10 Pa).

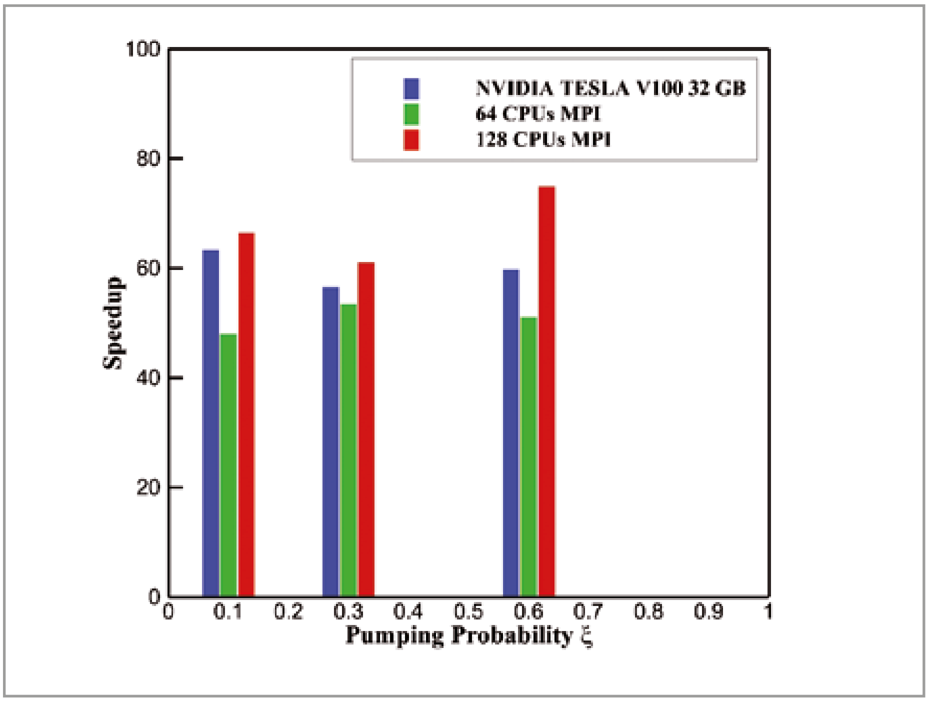


Fig. 7: Comparison of the accelerations through parallelisation with different computer architectures.

calculations usually carried out at the Institute, this means that the previously required access to the MARCONI supercomputer (Italy), which is often associated with long waiting times in the queue for the computing jobs, can be replaced in the medium term by a computer structure located at our Institute without noticeable performance losses.

Another very demanding application of our gas dynamic codes is the simulation of particle removal in the **W7-X** stellarator. For this, extensive calculations were carried out in 3D, for the first time ever. Figure 8 clearly shows that the divertor geometry cannot be mapped in 2D. To our knowledge, the DSMC method for solving the Boltzmann equation has never been used for such a complex geometry. The calculations are used to optimise plasma operation with new cryogenic pumps that will be connected in 2022.

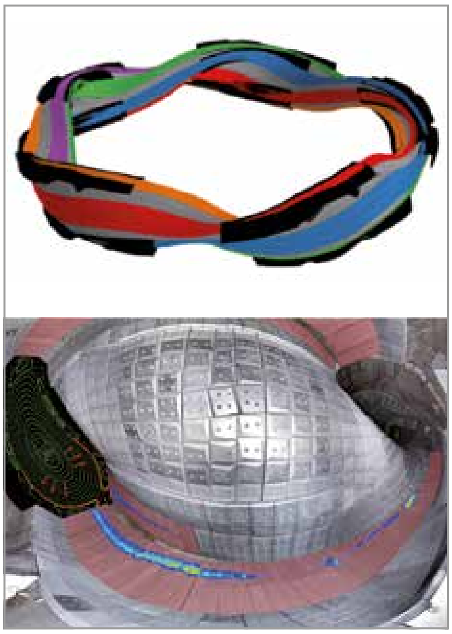


Fig. 8: Illustration of the surfaces to be modelled in the plasma vessel of W7-X.

Figure 9 shows the extracted model with the computational grid. The pump nozzles to which the vacuum pumps are connected can be clearly seen. The calculations have not yet been completed; however, it has already become clear that the influences of installation gaps and shields can be quantified. This collaboration will continue intensively for the next few years

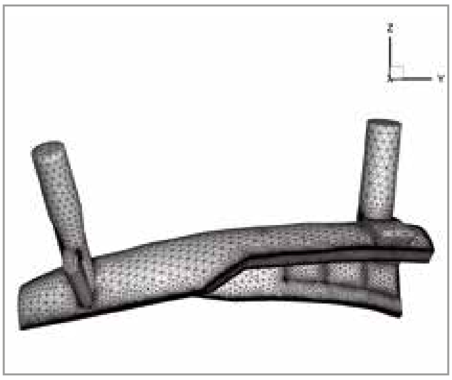


Fig. 9: Grid of the W7-X Divertor.

Contact: stylianos.varoutis@kit.edu

VACUUM HYDRAULICS AND HYDROGEN SEPARATION

The research topic “Vacuum Hydraulics and Hydrogen Separation” encompasses all work dealing with the flow behaviour of fluids, especially liquid metals, in machines and processes under vacuum. Accordingly, the ITEP’s Vacuum Technology Division is also working on processes for handling these working fluids, such as purification and processing of mercury, and on the development of associated analytical procedures. The reference concept for the torus vacuum system of the European demonstration fusion power plant DEMO provides for three different pump types. The first is the metal foil pump, which not only compresses the gas but also separates most of the unburnt fuel in the exhaust gas. Downstream, this is then followed by a combination of mercury-based high and coarse vacuum pumps. All three pump types are being developed in parallel up to the prototype stage at the Institute.

In order to be pumped, the hydrogen in the metal foil pump must be converted into an energetic state. For this task, a microwave plasma source is used, which should achieve a high degree of energisation. Following a modification to avoid the production of metallic impurities in the plasma, another major step towards long-term high permeation fluxes was achieved in 2021. Figure 10 shows the comparison of two permeation flux measurements in the HERMESplus test facility under the same experimental conditions (20 Pa, 900 °C niobium foil temperature and 2.4 kW plasma power). The differ-

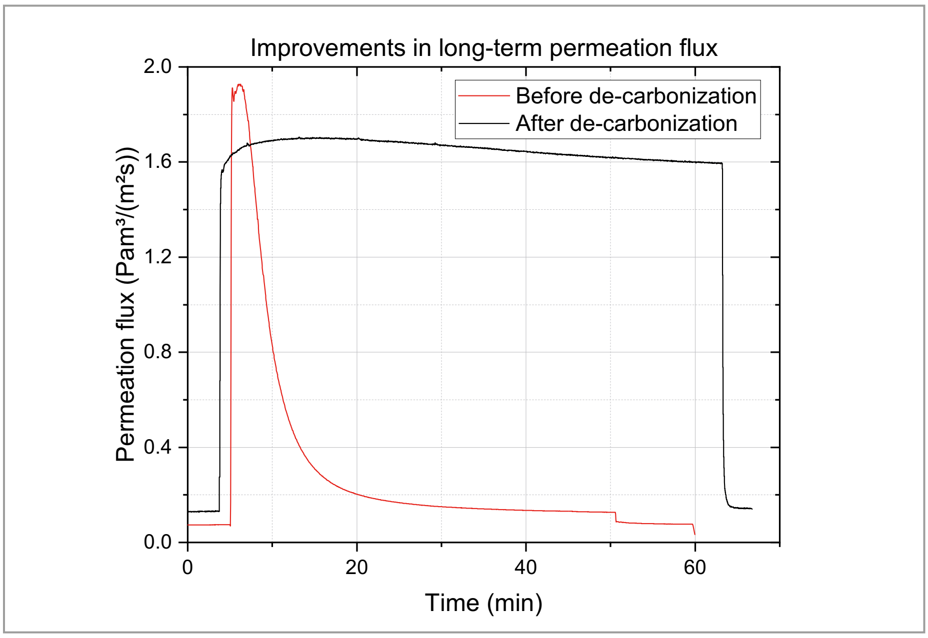


Fig. 10: De-carbonisation of the film is a prerequisite for achieving constant flux densities over a long period of time.

ence in the curves was achieved by de-carbonising the metal foil. In this process, carbon, which inhibits the diffusion of oxygen essential for superpermeation below the surface in the metal, is outgassed in the form of CO at high temperatures (approx. 1500 °C).

In parallel to the experimental work in HERMESplus, another activity was started that deals with the mechanical structure and manufcaturability aspects of a metal foil pump on a technical scale. Here, we are investigating how modular the pump can be designed. For example, the foil segments must (i) be mountable, (ii) be vacuum-tight and (iii) allow the foil to be heated uniformly by a direct current flow through the foil.

Downstream of the metal foil pump, linear mercury diffusion pumps shall be used. The working principle of such pumps is based on the momentum transfer of mercury vapour, which is accelerated to supersonic in nozzles, to the gas particles to be pumped. For a better understanding of the flow processes in the nozzle, a new experimental setup was realised in 2021, see Figure 11, which will go into operation next year in the mercury laboratory.

Another important point in the operation of mercury pumps is the reduction of backflow. For this purpose, optically tight, cooled baffles must be developed. Figure 12 shows a first design for this component and the particle trajectories when modelling the transmission probability in a Monte Carlo model.

To provide the fuel to the fusion plasm chamber 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 existing mixture of hydrogen isotopologues and extract the H that is unfavourable for the plasma reaction. For this purpose, a new method has been developed at the Vacuum Technology Division which is based on the concept of cyclic temperature swing absorption (TSA) on metals with opposite isotope effects. The gas mixture is cyclically moved back and forth between two col-

Fig. 11: Experimental set-up NEMESIS (Nozzle Experiment for Mercury Expansion Investigations).

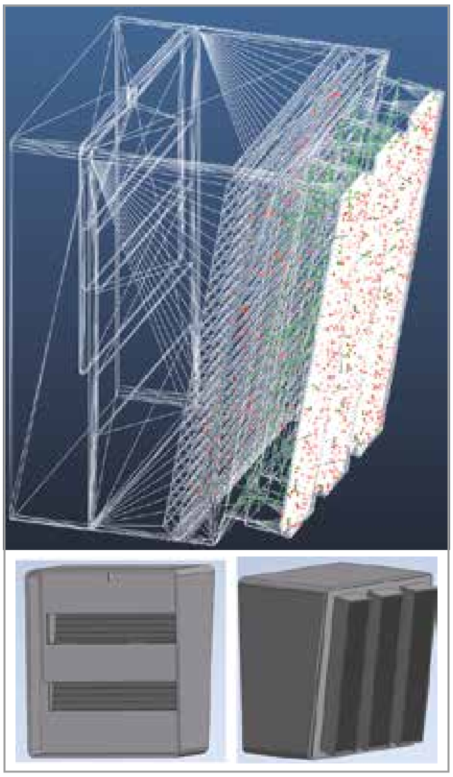


Fig. 12: Design and Model of a diffusion pump baffle.

umns in a semi-continuous process, whereby after a certain number of cycles an enrichment of the isotopes at the respective ends of the column takes place.

In 2021, this process was demonstrated for the first time at the HESTIA facility built for this purpose. Figure 13 shows a key result, namely the dependence of the achievable enrichment on the number of cycles. It was shown that an H2-D2 mixture of the initial composition 42%/58% could be enriched to over 65% (H2) or over 75% (D2), close to the equilibrium value specified by the material, in a single separation stage after only 3 cycles. This means that the total duration of this process in DEMO (consisting of several stages) can be significantly reduced.

The development work underway in this research topic qualifies new and innova-

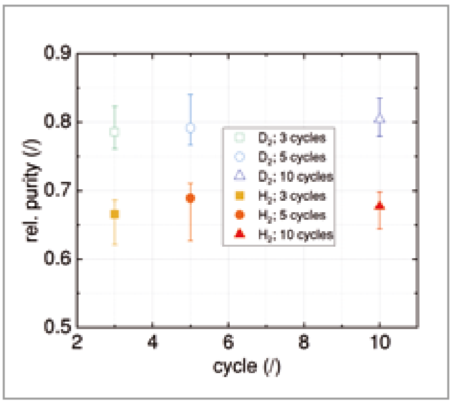


Fig. 13: Enrichment of the hydrogen isotopes in a TSA-process.

tive processes for use in DEMO's fuel cycle as part of a systematic technology development. In the next 3 years or so, all the new developments led at the Institute (metal foil pump, mercury vacuum pumps, temperature swing absorption process) will be ready for prototyping. The next logical step is then to build and test the individual prototypes in their interaction in the fuel cycle. In order to be able to correctly map the dynamics of the entire process, it is then necessary to realise the first two of the three fuel cycle loops completely, i.e. including the material supply via pellet injection. This requires a separate test environment. After a planning and application phase lasting several years, the **DIPAK** (Direct Internal Recycling Integrated Platform Karlsruhe) project was approved by the Executive Board in 2021 and endorsed by the Senate and the Supervisory Board. Funding for the facility from the EUROfusion programme has

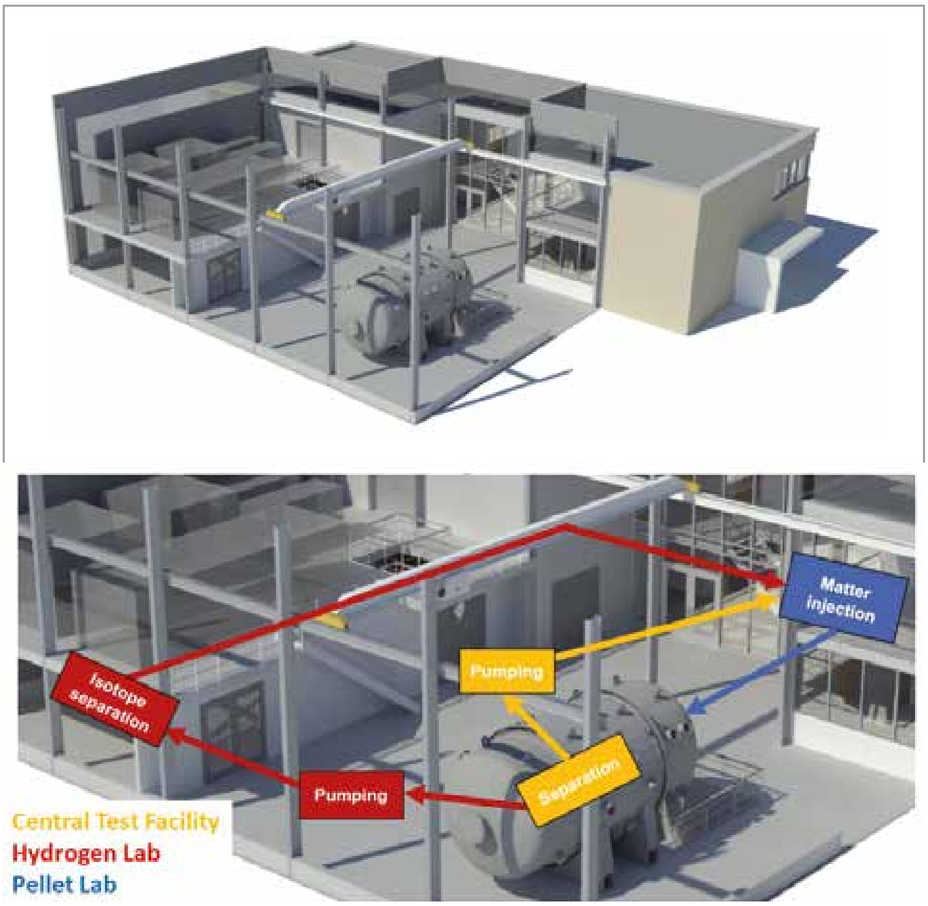


Fig. 14: Architecture of the DIPAK building (top) and overview of its main research infrastructures (bottom).

been received, as has approval been given from the Helmholtz Energy Programme. The document for the construction of the new DIPAK building on Campus North (Figure 14) is already in iteration with the corresponding KIT Department (Planning and Building, PB). The DIPAK project has thus been officially initiated.

The manufacturing drawings for DIPAK's complex central test vessel (Figure 15), which will simulate the torus of a future fusion power plant, have also already been prepared and approved by TÜV.

With regard to the Siemens PCS7-based control technology for DIPAK, which is very complex and must be completely set up and tested before moving into the DIPAK building, work has also already begun. This initially meant setting up the control hardware and the 1:1 scale (Figure 16) in building 416. The first components, for integration into the control technology, have already been installed (atomic adsorption spectrometer, Dräger sensors).

Kontakt: thomas.giegerich@kit.edu

Fig. 16: A look into the control technology development room for DIPAK.

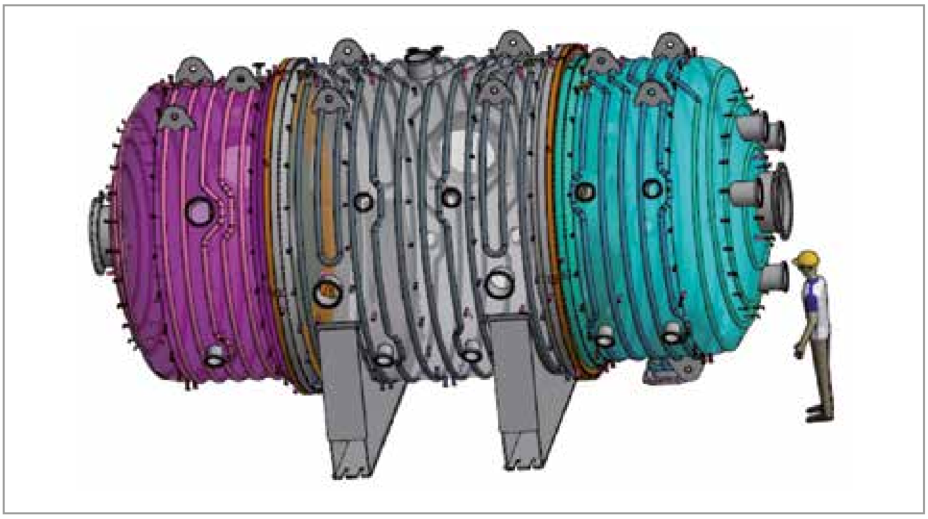


Fig. 15: The central test vessel of DIPAK.

Highlight
The tritium inventory fits

Seven years ago, the development of DEMO's fuel cycle started. At the time, it was believed that a simple extrapolation of ITER's fuel cycle would already be a good solution for DEMO.

In a first analysis, however, the researchers at ITEP had to realise that this would lead to an unacceptably large tritium inventory: Initial estimates led to significantly more than 10 kg of tritium, which was a 'show-stopper' in terms of the existing reserves and the associated safety aspects. The solution to this problem and the demonstration of the technical implementation is now the core task in the research field 'Technologies of the Fuel Cycle'.

In a first step, work was done on modifying the components of the fuel cycle so that the tritium inventories become significantly smaller. This initially meant switching from discontinuous cryopumping technology (as used at most fusion plants) to continuous mercury technology. However, the improvements achieved were not yet sufficient. Therefore, the entire architecture was redesigned, taking into account the functionality of fuel separation at the torus, and thus the possibility of quickly and directly recycling a large part of the unburnt fuel. Figure 17 shows the prediction at the time, which gave hope that the tritium inventories of ITER (4 kg) could also be realised for DEMO.

However, this still did not provide a solution, because there was no technology for the near-divertor separation of ultra-pure hydrogen for recycling. The next step was therefore to identify a technology that could solve the new task: this was the superpermeation of excited hydrogen on metal foils. The idea of a metal foil pump was born. In the meantime, we are on a very good path here.

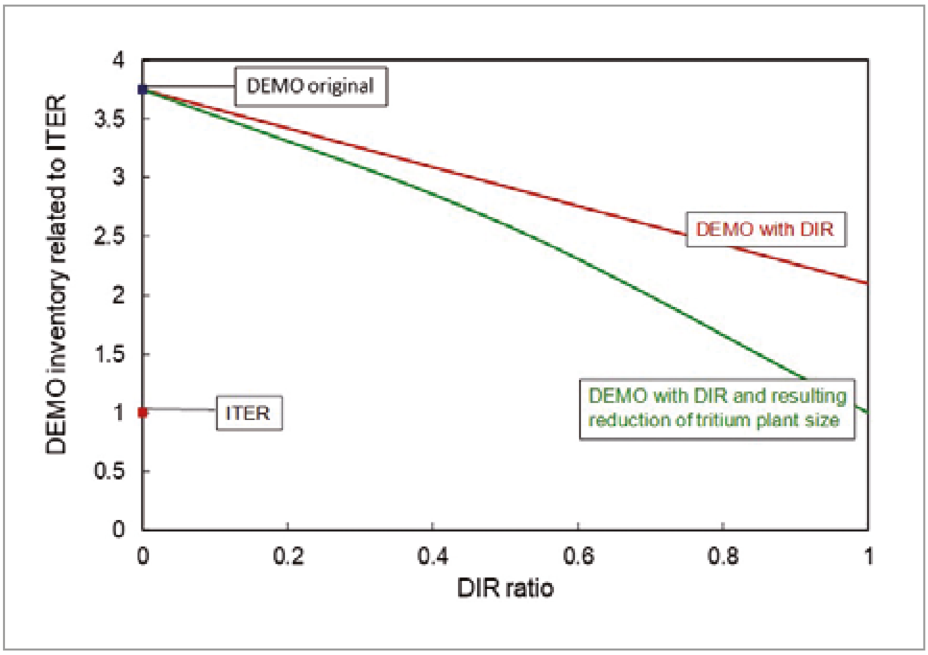


Fig. 17: Possibilities for inventory reduction by switching to the new fuel cycle architecture.

However, validating the goals with realistic process data for the new architecture of the fuel cycle now required the development of a software tool that can describe all the technologies in the fuel cycle, perform dimensioning, and then calculate the inventories. There was no satisfactory precursor for this in fusion either. A process simulator was therefore developed based on commercial software widely used in chemical plant construction, the Aspen Custom Modeller. Self-written software modules made it possible to completely describe the fuel cycle. Finally, in 2021, the individual system blocks in the fuel cycle had been investigated to the extent that the tritium inventory could be estimated. The result using the example of the water-cooled liquid lead blanket (WCLL) is shown in Figure 18.

It turned out that the operational tritium inventory is about 1.9 kg. To be added to this is the inventory in the first wall of the plasma vessel of another 1 kg and a tritium reserve of another 1 kg to compensate for any disturbances in operation at short notice. This brings the total to just under four kg, which is exactly the value already approved for ITER: Target achieved!

Having reached this important milestone, the entire team is now looking forward to further advancing the technical maturity of the new technologies and finally demonstrating the functioning of the fuel cycle in DIPAK.

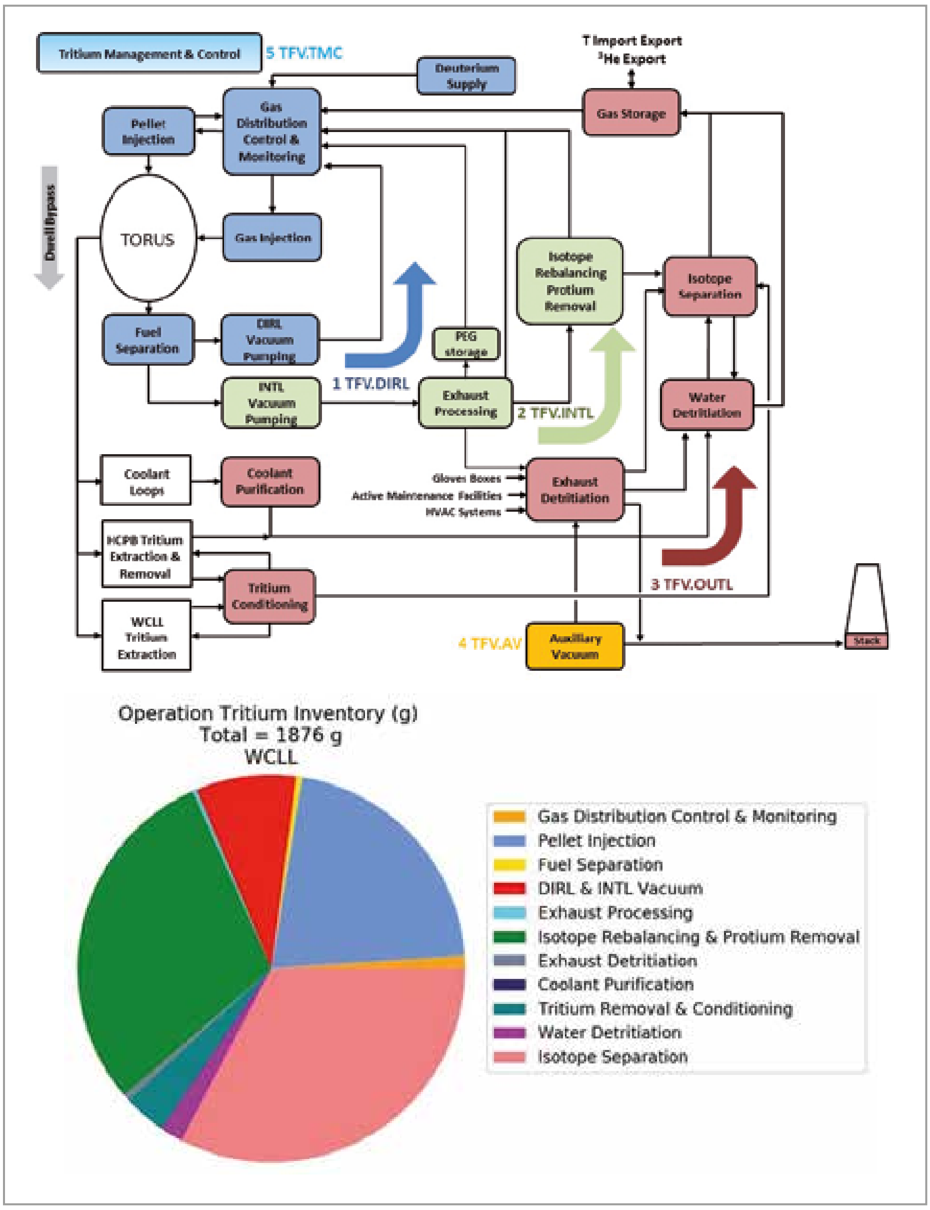


Fig. 18: Distribution of the operational tritium inventory (bottom) onto the individual system blocks (top) in steady-state operation of the fuel cycle (calculation for an assumed efficiency of the metal foil pump of 0.8).

Prizes and awards

In 2021, the following awards and prizes were presented for the work and to the employees of ITEP.

Fig. 1: View of Building 668 (Image Behnisch Architekten).

In September 2021, we were able to accept the **Hugo-Häring Prize of the Association of German Architects (BDA) for the Energy Lab 2.0 building, Building 668.** Among other things, the jury of the Hugo-Häring Prize appreciated the very successful arrangement of the areas and the visual connection of the different rooms. Building 668, which is shared with the Institute for Automation and Applied Computer Science (IAI), houses the ITEP's power hardware-in-the-loop laboratory and associated office workstations.

Mr. Stefan Biser, a PhD student supervised by us, received the **Best Paper Award** for his paper "Design Space Exploration Study of a distributed turbo-electric Propulsion System for a Regional Passenger Aircraft" at the AIAA/IEEE Electrical Aircraft Technologies Symposium. The paper exemplifies how a novel hybrid-electric propulsion system of an aircraft can be designed in an optimized way.

Fig. 2: Prof. Dr. Tabea Arndt

Prof. Dr. Arndt was appointed to the **Board of Trustees of the EnBW Foundation** by the President of KIT. With the help of this independent foundation, EnBW actively contributes to the success of the energy turnaround and climate protection and promotes corresponding initiatives and projects in this field.

Dr. Giovanni de Carne has started his **Helmholtz Young Investigator Group** on "Hybrid Networks: a multi-modal design for the future energy system". With this, Mr. de Carne receives a 5-year grant to establish his own research group in this field.

Fig. 3: Dr. Giovanni de Carne

We are very pleased about this recognition of these exceptionally good achievements of our staff and thank you very much for your excellent work.

Dr. Carl Bühler

Conductor Concepts for Grain Refinement in Nb_3Sn

Since the discovery of the internal oxidation method as a means to increase the critical current density of Nb3Sn-based conductors, performance improvements were almost exclusively explained by the observed grain refinement. The effect of nanoscale precipitates as artificial pinning centers that increase the performance of internally oxidized wires had rarely been addressed and little attention was paid to how the placement of the O- and Sn source-structures in relation to each other influence the phase formation and eventually the internal oxidation of the Nb alloy. The information that oxygen from filament designs with a mixed Sn and oxygen source structure first oxidizes the inter- mediary Nb-Sn intermetallics was therefore overlooked. Differences in grain size and pinning behavior of conductors of different designs were explained either by the lack of alloying element or a too thick Cu layer between the oxygen source structure and the to-be-oxidized Nb alloy. No conclusive mechanism had been found to explain why some conductor concepts show grain refinement and others do not.

Within this work, it could for the first time, be demonstrated how the filament design and therefore the separation between Sn- and O diffusion influences the phase formation, the Nb_3Sn grain size as well as the generation of nanoscale precipitates:

In conductor concepts with a mixed Sn- and O source-structure, it was found that the outward diffusion of oxygen is delayed when intermediary Nb-Sn intermetallics are oxidized. This in turn delays the oxidation of the alloying element in the reaction tube so that oxidic precipitates are only generated after Nb_3Sn has already formed. This way, no grain refinement occurs and the solubility of the alloying element in the formed Nb_3Sn limits the generation of precipitates. Even without grain refinement, it was demonstrated that such precipitates act as performance increasing pinning centers and that a regular PIT powder core already contains enough oxygen to oxidize the alloying element remaining in the Nb_3Sn. As the amount of precipitates is limited by the solubility of the to-be-oxidized alloying element in Nb_3Sn, the only factor influencing the pinning properties of the superconducting phase is the choice of the Nb-alloy.

For binary alloys such as Nb1Zr, high point pinning contributions of more than 50 % were meas- ured. For ternary alloys like Nb7.5Ta1Zr of Nb7.5Ta2Hf, the point pinning contribution was in- creased to ~30 %. In Nb7.5Ta1Zr samples a non-Cu J_c of 1222 A/mm² at 16T was measured, a 13 % increase compared to the 1122 A/mm2 of a representative PIT wire.

In conductor concepts with separated, concentric Sn- and O source-structures, the formation of Nb-Sn intermetallics is delayed so that oxygen can diffuse directly into the Nb-alloy. This causes a higher amount of oxygen to dissolve form precipitates in the Nb alloy. Indications for this are visible in the suppressed recrystallization of the Nb alloy after 300 h at 640 °C as well as a 2.1 K drop of the Nb-T_c after heat treatment. In accordance with the first reports of a successful grain refinement it was shown that a time-wise separation of the oxidation and Nb-Sn phase for- mation is required to obtain significantly refined Nb_3Sn.

Reports that the recrystallization of the Nb-alloy precursor at final diameter can be suppressed without the implementation of an oxygen source could not be confirmed. Although a sup- pression of the recrystallization in the Nb-alloy after 300 h at 640 °C correlated with a refined grain size, no general causation between the grain size of the Nb-alloy and the formed Nb_3Sn was observed. Therefore, it is concluded that the suppression of the recrystallization of the Nb alloy is only indicative of the presence of nanoscale precipitates in the Nb alloy precursor due to a successful oxygen transport. It is not the cause of the grain refinement of the formed Nb_3Sn.

Dr. Shahab Karrari

Integration of a flywheel mass storage system in low-voltage distribution networks

A flywheel energy storage system (FESS) can rapidly inject or absorb large amounts of power to support the grid following an abrupt change in generation or con-sumption. In addition to a fast response time, a FESS has the advantage of a high power density and a large number of charge and discharge cycles without capaci-ty loss throughout its lifetime. These characteristics make the FESS a well-suited candidate for grid fre-quency stabilization or balancing short-term power fluc-tuations at the local level.

In this dissertation, the grid integration of a high-speed FESS at the low-voltage level is investigated from sev-eral perspectives. First, the problem of placing and sizing a FESS in low-voltage distribution networks for power balancing applications is addressed. In order to find the most suitable location for a FESS, a data-geared method for estimating the relative voltage sensi-tivity is presented, based on the concept of mutual-information. The main advantage of the proposed meth-od is that it does not require a network model and uses only measured values at the points of interest. Meas-urement results from a real grid in southern Germany show that the proposed approach can successfully allocate the grid connection points with higher voltage sensitivity to active power changes, which can benefit most from a smoother power profile enabled by FESS.

In addition, a new method for dimensioning energy stor-age systems using measured data is introduced. The proposed approach identifies recurring consumption patterns in recorded power profiles using the Motif Dis-covery algorithm, which are then used to size different storage technologies, including a FESS. Using collected measurement data from several low-voltage grids in Germany, it is shown that the storage systems can be effectively used for their applications using the charac-teristics derived from the detected patterns throughout the measurement period.

Next, a dynamic real-time model of a high-speed FESS was developed and validated with experimental results in several scenarios, taking into account the losses and auxiliary power demand of the system. In the scenarios studied, a maximum difference of only 0.8% was ob-served between the charge level of the model and the real FESS, which describes the accuracy of the devel-oped model.

After determining the required setup, the performance of a 60 kW high-speed FESS was evaluated during several frequency deviation scenarios using power hardware-in-the-loop tests (PHIL). The results of the PHIL tests show that the high-speed FESS responds very quickly after a sudden frequency deviation, reaching the re-quired power in just under 60 ms, while meeting the latest requirements of the application rules for frequen-cy support at the low-voltage level.

Finally, to deemonstrate the benefits of the fast re-sponse of the FESS for low inertia power systems, a novel adaptive inertia emulation controller for the high-speed FESS was introduced and its performance in a low-inertia microgrid was validated through simulations and experiments. The simulation results show that the use of the FESS with the proposed inertial emulation controller can reduce the maximum rate of change of frequency by 28% and the maximum frequency devia-tion by 44% during islanding of the studied microgrid, and outperforms several previously presented adaptive control schemes. The proposed controller was also implemented on a real 60 kW FESS using the concept of rapid control prototyping, and the performance of the FESS with the new control design was validated using PHIL tests of the FESS. The PHIL results, which rep-resent the first-ever experimental validation of inertial emulation with a FESS, confirm the simulation results and demonstrate the advantages of the proposed con-troller.

Fig. 1: 60 kW Flywheel energy storage system in Pow-er-Hardware-in-the-Loop test facility

Lectures, Seminars, Workshops

Lectures

KIT-Fakultät Elektrotechnik und Informationstechnik

- **Supraleitende Systeme der Energietechnik** (Holzapfel, Noe) WS 20/21
- **Supraleitende Materialien** (Holzapfel, Hänisch) WS 20/21
- **Energy Storage and Network Integration** (Noe, Grilli, De Carne) WS 20/21
- **Übungen zu Energy Storage and Network Integration** (Noe, Grilli, De Carne, Kottonau, Karrari) 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) SS 20

KIT -Fakultät für Chemieingenieurwesen und Verfahrenstechnik

- **Vakuumtechnik** (Day) WS 20/21
- **Übung zu Vakuumtechnik** (Day, Varoutis) WS 20/21
- **Kältetechnik A** (Grohmann) WS 20/21
- **Übungen zu Kältetechnik A** (Grohmann, Mitarbeiter) WS 20/21
- **Cryogenic Engineering** (Grohmann) WS 20/21
- **Cryogenic Engineering-Exercises** (Grohmann, Mitarbeiter) 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 20/21
- **Fusionstechnologiekolloquium*** (Noe) SS 20
- **Magnet-Technologie für Fusionsreaktoren** (Fietz, Weiss, Wolf) SS 20
- **Vakuumtechnik und Tritiumbrennstoffkreislauf** (Day, Frances, Größle) SS 20

House of Competence

- **„Netzwerken – Verbindungen schaffen Freiheiten“** (Arndt) WS 20/21

Seminare

Kryo-Seminare

- **22.–24.9.2021 VDI-Wissensforum „Kryotechnik“** (Kläser)

Duale Hochschule BW – Fachbereich Maschinenbau

- **Arbeitssicherheit und Umweltschutz** (Bauer) SS 20
- **Thermodynamik 1 für Maschinenbauer** (Neumann) SS 20
- **Thermodynamik 2 für Maschinenbauer** (Neumann) SS 20
- **Tieftemperaturtechnik** (Neumann) WS 20

Zhejiang-Universität (China)

- **14.07.–25.08. CryogenicsOnline-Vorlesung** (10 Termine à 2 Zeitstunden) (Neumann) SS 20

Harbin Institute of Technology (China) – Summer School*

- 16.07.2021 **(High) Magnetic fields by superconductors** (Arndt)

PhD Theses

(* Academic supervisor; ** completed)

ENERGY

Gabriele Arena
Development and testing of a multi-modal hardware in the loop setup
Betreuer: Dr.-Ing. G. de Carne, Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Fargah Ashrafidehkordi
Impedance-based stability and accuracy analysis of a Power-Hardware-In-Loop evaluation
Betreuer: Dr. G. de Carne, Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Stefan Biser
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
Prospective Life Cycle Assessment of High-Temperature Superconductors for Future Grid Applications
Betreuer: Dr. M. Weil (ITAS), Prof. Dr.-Ing. M. Noe*

Maëva Courcelle
Development of an on-line load sensitivity identification microcontroller toolbox
Betreuer: Dr. G. de Carne, Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Shahab Karrari **
Integration of Flywheel Energy Storage Systems in Low Voltage Distribution Grids-
Betreuer: Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Ali Khonya
Superconducting electrical propulsion system modelling
Betreuer: Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

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

Masoome Maroufi
Real time modelling of hybrid networks-
Betreuer: Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Philipp Müller
Theoretische und experimentelle Untersuchung des Wechselstromverhaltens supraleitender Wicklungen für die Anwendung in rotierenden Maschinen Betreuer: Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Quoc Hung Pham
Untersuchung von schnellen Schaltvorgängen in Hochtemperatur-Supraleitern-
Betreuer: Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Karthik Rajashekaraiah
Echtzeit Modellierung von hybriden Netze
Betreuer: Dr. G. de Carne, Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Carsten Räch
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)*

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

Qiucen Tao
Smart demand controllers for multi-modal networks Betreuer: Dr. G. de Carne, Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

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

MAGNET

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

Kirtana Phutran
Cable and winding concepts for 20 T HTS dipole accelerator magnets
Betreuer: Prof. Dr. T. Arndt (KIT, ETIT)*

MATERIAL

Kai Ackermann
Flussliniendynamik in *RE*BCO-Schichten im Bereich des *Glass-Liquid*-Phasenübergangs
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel (KIT, ETIT)

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

Wolfram Freitag
Optimierung eines kontinuierlichen Prozesses zur Herstellung REBa2Cu3O7x-basierter supraleitender Bandleiter aus chemischen Präkursorenlösungen-
Betreuer: Prof. Dr. B. Holzapfel, Prof. Dr.-Ing. J. Sauer (IKFT)*

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

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

Stylianos Tokatlidis
Influence of transition metal doping on the electrical transport properties of Fe (Se, Te) thin films
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel (KIT, ETIT)*

VAKUUM

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

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

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

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

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

Tim Teichmann
Entwicklung eines Berechnungsverfahrens für quecksilbergetriebene Vakuumpumpen in einem weiten Bereich der Knudsenzahl-
Betreuer: Dr. C. Day, Prof. Dr. R. Stieglitz (KIT, Mach)*

Annika Uihlein
Entwicklung eines Temperaturwechselabsorptionsverfahrens zur Trennung von Wasserstoffisotopen im FusionsbrennstoffkreislaufBetreuer: Dr. C. Day, Prof. Dr. R. Stieglitz (KIT, Mach)*

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

Master Theses

(* Academic supervisor; ** completed)

Maëva Courcelle   **
Construction of a data communication connection between a real-time simulator and an external energy system plant on a Modbus protocol basisBetreuer: D. Kottonau, Prof. Dr.-Ing. M. Noe*

Mateusz Krawczyk   **
Comparison of two numerical formulations for modelling the electromagnetic behaviour of high-temperature superconducting tapes for power cables
Betreuer: PD Dr. F. Grilli*

Philipp Müller   **
Konzeptionelle Auslegung supraleitender Bahntransformatoren
Betreuer: Prof. Dr.-Ing. M. Noe*

Marco Öhl   **
Lehrmodelle des Elektromotors. Entwicklung, Konstruktion und Fertigung mit dem 3D-Drucker
Betreuer: A. Rimikis / Prof. Dr. Dipl.-Psych. I. Langemeyer (KIT)*

Kevin Raczka   **
Concept design of the divertor pumping system for the Divertor Tokamak test Facility
Betreuer: Dr. C. Day, Prof. Dr. R. Stieglitz (KIT, MACH)*

Stefanelli Lorenzo
Identification of a Real Micro Gas Turbine based on Rowen's modelBetreuer: D. Kottonau, Prof. Dr.-Ing. M. Noe*

Felix Wald
Controller-Hardware-in-the-Loop and Power-Hardware-in-the-Loop Testing of a Virtual Synchronous Machine for Asynchronously Connected Grids
Betreuer: Dr. G. de Carne / Prof. Dr.-Ing. M. Noe*

Johannes Weis
Determination of the thermal resistance between metallic surfaces of copper and stainless steel for high current HTS Cable-in-Conduit Conductor
Betreuer: Dr. N. Bagrets, Prof. Dr. B. Holzapfel

Alexander Zilz
Untersuchung der verdünnten Gasströmung im Pumprohr eines 3He/4He Mischungskryostaten
Betreuer: Dr. Tantos / Prof. Dr.-Ing. S. Grohmann (ITTK)*

Bachelor Theses

(* 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 **
Numerische Modellierung von supraleitenden Magneten aus YBCO Bandleitern
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel*

Julian Bell
Entwicklung eines didaktischen Konzepts für die Experimentierstation
Betreuer: A. Rimikis / Prof. Dr. B. Holzapfel*

Katrin Bitzer **
Modellierung des resistiven Phasenübergangs von supraleitenden Dünnschichten
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel*

Leo Burger **
Untersuchung zur Optimierung der Prozessparameter bei der Herstellung supraleitender ErBCO-Dünnschichten auf IBAD-Substraten mittels Definitve Screening-Versuchsplänen
Betreuer: W. Freitag, Dr. J. Hänisch*

Nicolas Dworschak
Entwicklung eines didaktischen Konzeptes für die Experimentierstation „Brennstoffzelle" im KIT-Schülerlabor Energie
Betreuer: A. Rimikis / Prof. Dr. B. Holzapfel*

Daniel Freerichs **
Herstellung und Untersuchung von Dünnschichten des Perowskits Nd0,8Sr0,2NiO3
Betreuer: K. Ackermann, Prof. Dr. B. Holzapfel*

Manuel Heinzelmann **
3D-Druck von tieftemperaturbeständigen Bauteilen mit dem Hochleistungspolymer PEEK
Betreuer: Dipl.-Ing. S. Bobien, Dipl.-Ing. T. Schneider* (DHBW)

Simon Martz **
Experimentelle Untersuchung des Schaltverhaltens von Hochtemperatur-Supraleitern bei wechselndem Magnetfeld
Betreuer: Q. Pham, Prof. Dr.-Ing. M. Noe*

Jonas Mensinger **
Optimierung der Prozessparameter zur Herstellung supraleitender *RE*BCO-Dünnschichten auf IBAD-Substraten mittels statistischer Versuchsplanung
Betreuer: W. Freitag, Dr. J. Hänisch*

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: Prof. Dr. E. Gottwald, Prof. Dr. Sauer (IKFT)*

Michael Temmen **
Deposition und Charakterisierung von Strontium-Neodym-Nickelat-Schichten
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel*

Figures and Data

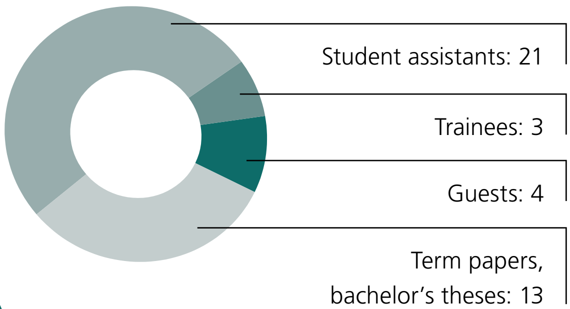
Chart of Organization

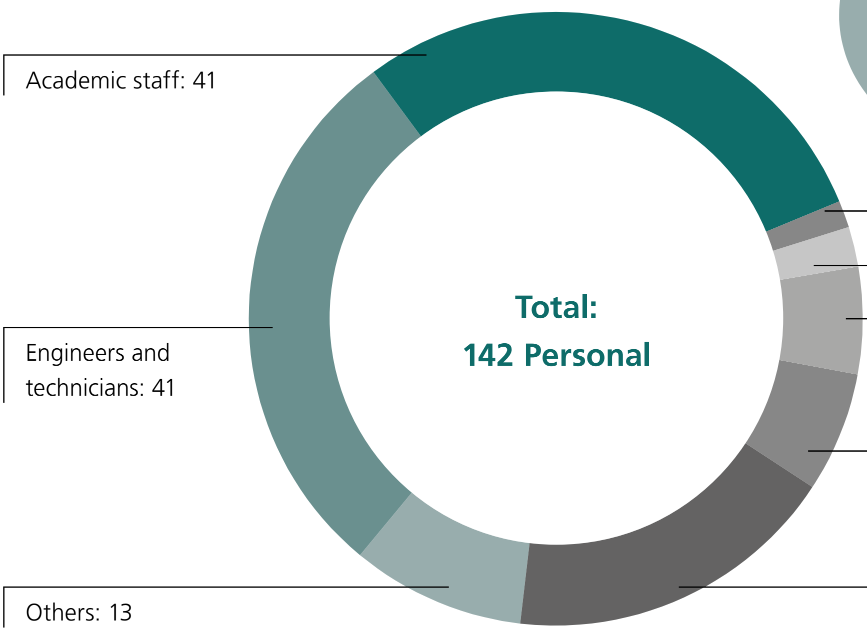
Superconducting and Cryomaterials (Holzapfel)	**Energy Applications** (Noe)	**Superconducting Magnet Technology** (Arndt)	**Fusion Fuel Cycle Technologies** (Day)
Superconducting Materials (Hänisch)	Superconducting Power System Components (Noe)	Coil and Magnet Technology (Hornung)	Vacuum Technology and Process Integration (Day)
Conductor Concepts and Technologies (Holzapfel)	Modelling of Superconductors and Components (Grilli)	High Current Components for H_2 and Fusion (Wolf)	Rarefied Gas Dynamics (Varoutis)
Materials for Cryogenic Applications (Weiss)	Real-Time System-Integration (De Carne)	Rotating Machines (Arndt)	Vacuum Hydraulics and Hydrogen Separation (Giegerich)

Personnel Status (m/f/d)

(December 31, 2021)

Additional staff in 2021:





Personnel Changes

Newly Recruited*

Gabriele Arena

Fargah Ashrafidehkordi

Maëva Courcelle

Asef Ghabeli

Ali Khonya

Paul Kruse

Masoome Maroufi

Philipp Müller

Karthik Rajashekaraiah

Dietrich Riegel

Camelia Schulz

Valerij Selskij

Othmann Taalibi

Qiucen Tao

Stylianos Tokatlidis

Annika Uihlein

Paul Walter

Leaving*

Hans Chen

Horst Haas

Reinhard Heller

Manuel Heinzelmann

Andrea Kling †

Philip Kreideweis

Yingzhen Liu

Jürgen Rössler

Michael Stamm

* (Excluding Trainees, Guests, and Student Assistants)

Student assistants

Dominic Barthlott

Johanna Bobien

Maëva Courcelle

Leonhard Döring

Farouk Haidar

Fabian Henßler

Vadim Mai

Philipp Müller

David Kubeneck

Ziyang Li

Patrik Lison

Simon Martz

Samuel Nick

Lars Ohnemus

Anantha Padmanabhan

Yassin Rahman

Nikolas Rimikis

Michael Temmen

Emanuel Weiss

Lukas Wirth

Jan Zudock

Guest Researcher

F. Huber
15.08.21–31.10.21
University of Strathclyde,
Glasgow, Schottland

P. Zhou
23.08.21–22.08.23
Southwest Jiaotong University,
Chengdu, P.R. China

J. Zhang
26.10.21–31.10.22
Southwest Jiaotong University,
Sichuan, P.R. China

J. Shi
23.10.21–31.10.22
Southwest Jiaotong University,
Sichuan, P.R. China

Memberships

of relevant technical and scientific organisations

Tabea Arndt

- Program Committee Annual Meeting FVEE, "With hydrogen to climate neutrality – from research to application", 10.-11.11.2021, Berlin
- Program committee of the conference ZIEHL, 04.-05.04.2022, Berlin
- International Organizing Committee Conference Magnet Technology, MT27, Fukuoka, Japan (virtual), 15.-19.11.2021
- Member DKE TC90
- Delegate to the Technology Cooperation Program High-Temperature Superconductivity of the International Energy Agency
- Member of the Magnet Panel of the Muon Collider Activity, CERN
- Member of the Board of Trustees of the EnBW Foundation
- "Research Field High-Temperature Superconductivity" of the BMWi, curator since end of 2021

Nadja Bagrets

- Expert within the TWA16 field of work of VAMAS (Versailles Project on Advanced Materials and Standards at ISO) for the performance of interlaboratory tests.
- Expert in Committee K 184 "Superconductors" of the German Commission for Electrical Engineering (DKE) at DIN
- Expert in the Technical Committee TC90 "Superconductors", Working Group WG5 of the International Electrotechnical Commission (IEC)

Kai Bauer

- Member of the Helmholtz-working group of the HSE „Health, Safety and Environment"
- Member of the examination boards of the Baden- Württemberg Cooperative State university, Karlsruhe, in the programmes of "Mechanical Engineering" and "Business Engineering"

Christian Day

- Member of the Executive Board of the German Vacuum Society (DVG).
- Project leader „Tritium-fuelling-vacuum" of the EUROFUSION
- Member of Fusion For Energy – Technical Advisory Panel
- Spokesperson of the Topic 'Vakuum and Tritium' of the German DEMO Initiative
- Member of the International Advisory Committee RGD (Rarefied Gas Dynamics Conference)
- Member of the Program Committee of the ISFNT (international Symposium of Fusion Nuclear Technology).
- Chartered Engineer of the American Vacuum Society (AVS).
- Member of the Steering Committee JT-60SA
- Board Member of the IAEA Technical Meeting Series on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy

Giovanni de Carne

- Helmholtz Young Investigator Group Leader – 2020
- Chairman der IEEE PES Task Force "Solid State Transformer integration in distribution grids"
- Secretary and Member of the CIGRE Working Group B4.91 "Power electronics-based transformer technology, design, grid integration and services provision to the distribution grid"
- Member of the CIGRE Working Group A3.40 "Technical requirements and field experiences with MV DC switching equipment"
- Member of the IEEE Working Group P2004 on "Hardware in the Loop".
- Member of the IEEE Working Group on "Modelling and Simulation with High Penetration of Inverter-Based Renewables"
- Associate Editor of the "IEEE Open Journal for Power Electronics"
- Associate Editor of the "IEEE Industrial Electronic Magazine"
- Associate Editor of the Springer Journal "Electrical Engineering – Archiv für Elektrotechnik"
- Member of the „Institute of Electrical and Electronics Engineers"
- Member of the „Verband der Elektrotechnik, Elektronik und Informationstechnik"

Walter H. Fietz

- Member of the "International Organizing Committee of Symposium of Fusion Technology (SOFT) conference"
- Program Comittee Member of HTS4Fusion Conductor Workshop
- IEEE Senior Member
- Member of the "IEEE Council of Superconductivity"

Thomas Giegerich

- Chairman of the Vacuum Physics and Technology Division of the German Physics Society (DPG)

Jens Hänisch

- Superconductor Science and Technology, Editorial board member
- European Magnetic Field Laboratory EMFL, User Proposal Selection Committee member
- Applied Superconductivity Conference, Materials programme committee member
- KIT-Convent

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, Member of International Program Committee
- European Conference on Applied Superconductivity, Member of International Programme Committee
- International Symposium on Superconductivity (ISS), Member of International Programme Committee

Holger Neumann

- Member of the ICE Commitee
- Board member of the Cryogenic Engineering Conference CEC since 2019
- Chairman of the DKV
- Guest professor in China at Zhejiang University in Hangzhou

Mathias Noe

- Trustee of the High-temperature Superconductivity Research Network of the BMWi
- International Expert of the CIGRE D1 69 working group "Assessing Emerging Test Guidelines for HTS Applications in Power Systems
- International Expert of the CIGRE D1 64 "Cryogenic Dielectric Insulation"
- German representative of the International Energy Agency, Technology Cooperation Program high-temperature superconductivity
- Member of the Board of the Applied Superconductivity Conference
- Member of the industrial association for superconductivity (ivsupra)
- Member of the working group for the creation of an accelerator R&D roadmap in the framework of a European strategy for particle physics.

Sonja Schlachter

- Member of the "International Cryogenic Material Conference (ICMC) Board of Directors"

Stylianos Varoutis

- Member of the Scientific Committee of the NEGF (European Conference on Non-equilibrium Gas Flows).
- Member of the Selection Committee of the EU High Performance Computer MARCONI
- Member of the Joint EU-JA Allocation Comittee for Computer Simulation under the Broader Approach
- Member of the German Vacuum Society (DVG)

Klaus-Peter Weiss

- DKE German Commission for Electrical Engineering, Electronics, and Information Technology of DIN and VDE Committee K 184 „Superconductors", Chairman
- IEC International Electrotechnical Commission/Technical Comittee 90 „Superconductivity", member of WG 2 „Critical current measurement of Nb-Ti composite superconductors", WG 5 „Tensile test and electro-mechanical 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"
- Spokesperson of the working group „Magnet Design" of the German coordination body for fusion research for DEMO
- Member of the International Technical Program Committee - MEM18 9th Workshop on Mechanical and Electromagnetic Properties of Composite Superconductors / Organizer MEM20 10th Workshop in Karlsuhe
- Board Member ICMC (International Cryogenic Materials Conference) Subcommittee International Cryogenic Material Library
- Expert within the EUROfusion Scientific & Technical Advisory Committee (STAC)

Publications

Fusion

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Journal article

* Heller, R., Fietz, W. H., Hamada, K., et. al.
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* Grilli, Francesco
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* Grünewald, Lukas, Nerz, Daniel, Langer, Marco, et. al.
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* Noe, Mathias, Kottonau, Dustin
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* Riva, Nicolo, Grilli, Francesco, Sirois, Frederic, et. al.
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* Schreiner, Fabian, Liu, Yingzhen, Noe, Mathias"
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* Yan, Yufan, Qu, Timing, Grilli, Francesco"
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* Grünewald, Lukas, Langer, Marco, Meyer, Sven, et. al.
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Proceedings

* Grilli, Francesco, Abraham, Sunny, Brambilla, Roberto
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Book essay

J. Hänisch, S.C. Wimbush
High-Temperature Superconductors, in: J. Rumble (ed), CRC Handbook of Chemistry and Physics, 102nd edition, CRC Press, 2021

Energy System Design (ESD)

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* Batista de Sousa, Wescley Tiago, Shabagin, Eugen, Kottonau, Dustin, et. al.
An open-source 2D finite difference based transient electro-thermal simulation model for three-phase concentric superconducting power cables
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Invited Papers

Tabea Arndt

- Tabea Arndt, Ressourcen und Energieeffizienz für die Energiewende, Online-Perspektiv-Tag „Karriere im Energiesektor" von Jugend forscht, Virtuell, 02.03.2021
- Tabea Arndt, (High) Magnetic fields by superconductors – from an early promise to present devices and new options, Summer School Harbin Institute of Technology, CN, virtuell, 16.07.2021
- Tabea Arndt, Mathias Noe, Plenary talk: Superconductivity for Green Energy, EUCAS 2021, 05.–09.09.2021, Moscow, RU, Moskau, virtuell, 06.09.2021
- Tabea Arndt, Wasserstofftechnologie und Fahrzeuge, FVEE Jahrestagung 2021, Berlin, 11.11.2021
- Tabea Arndt, Electric machines based on HTS – selected aspects and recent developments, ISS 2021, JP, Fukuoka (teil-virtuell), 01.12.2021

Katharina Battes

- Katharina Battes, Current design status and outgassing considerations for the vacuum system of the Einstein Telescope, Virtual DPG Meeting, 27 Sept – 1 Okt. 2021
- Katharina Battes, Overview of the Outgassing Behavior of Metals, Polymers and Ceramics, Annual Symposium of the American Vacuum Society, Virtuell, 25–28. Okt. 2021
- Katharina Battes, Outgassing considerations for the cryogenic vacuum system of the Einstein Telescope, European Vacuum Conference, Marseille, France, 21–26 Nov 2021

Christian Day

- Christian Day, More loops, less inventory – a smart three-loop architecture for the fuel cycle of a fusion power plant, Plasma Seminar at MIT, 21 September 2021
- Christian Day, Vacuum Technology for Fusion Research, Annual Symposium of the American Vacuum Society, Virtuell, 25–28. Okt. 2021

Volker Hauer

- Volker Hauer, IFMIF-DONES gas flow modelling using Test Particle Monte-Carlo Simulations, Virtual DPG Meeting, 27 Sept – 1 Okt. 2021

Jens Hänisch

- Growth, microstructure and pinning properties of CSD *RE*BCO films and nanocomposites, CEC-ICMC, Virtuell, 19. Juli 2021

Christos Tantos

- Christos Tantos, Deterministic modeling of neutral gas flows of tokamak nuclear fusion devices, Virtual DPG Meeting, 27 Sept – 1 Okt. 2021

Tim Teichmann

- Tim Teichmann, Stochastic Simulation of Mercury Diffusion Pumps Using Direct Simulation Monte Carlo, Virtual DPG Meeting, 27 Sept – 1 Okt. 2021

Stylianos Varoutis

- Stylianos Varoutis, Deterministic and stochastic numerical approaches in Rarefied Gas Dynamics, Virtual DPG Meeting, 27 Sept – 1 Okt. 2021

Patents Held

* New IP applications in 2021; ** IP rights granted with effect in Germany in 2021

- Kryostat mit einem Magnetspulensystem, das eine LTS- und eine gekapselte HTS-Sektion umfasst
  Kläser, Marion
  US 8255023

- Kryostat mit einem Magnetspulensystem, das eine unterkühlte LTS- u. eine in einem separaten Heliumtank angeordnete HTS-Sektion umfasst
  Schneider, Theo
  US 8255022

- Vorrichtung zur Strombegrenzung mit einer veränderbaren Spulenimpedanz
  Noe, Mathias; Schacherer, Christian
  DE 2532016
  FR 2532016
  GB 2532016
  JP 5907894
  US 9583258

- Isolierter Hochtemperatur-Bandsupraleiter und Verfahren zu seiner Herstellung
  Brand, Jörg; Elschner, Steffen; Fink, Stefan; Goldacker, Wilfried; Kudymow, Andrej
  AT 2729969
  CH 2729969
  DE 2729969
  FR 2729969
  GB 2729969
  IT 2729969
  KR 10192955
  US 939840

- Verfahren und Vorrichtung zur kontinuierlichen Wiederaufbereitung von Abgas eines Fusionsreaktors
  Day, Christian; Giegerich, Thomas
  CN 105706175
  DE 3061098
  FR 3061098
  GB 3061098
  KR 1020167007345

- Design of Superconducting Devices By Optimization Of The Superconductor's Local Criticial Current
  Holzapfel, Bernhard; Rodriguez Zermeno, Victor
  DE 2983218
  US 10153071

- Schienengebundene Magnetschwebebahn
  Holzapfel, Bernhard; Noe, Mathias
  CN 2016800101353
  DE 3256359
  DE 102015001746.2
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  US 10604898

- Transformator, Wickelkörper dafür und Verfahren zur Herstellung eines Wickelkörpers
  Hellmann, Sebastian
  DE 3341945
  FR 3341945
  GB 3341945

- Supraleitfähiger Leiter und Verwendung des supraleitfähigen Leiters
  Fietz, Walter; Heller, Reinhard; Weiss, Klaus-Peter; Wolf, Michael J.
  CN 10814458
  DE 102015010636.8
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- Verbinder für supraleitfähige Leiter und Verwendung des Verbinders
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  CH 3335280
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  DE 102015010634.1
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- Verfahren und Vorrichtung zur Herstellung eines supraleitf higen Leiters
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  CN 201680059670.8
  DE 102015010676.7
  EP 16756943.3-1212
  US 15/752,224

- Design of contacts for superconducting busbars and cables
  Rodriguez Zermeno, Victor
  DE 3352303
  FR 3352303
  GB 3352303

- Verfahren und Vorrichtung zur Anreicherung oder Abreicherung mindestens eines Wasserstoffisotops in einem Gasstrom
  Day, Christian; Giegerich, Thomas; Hörstensmeyer, Yannik; Müller, Ralf; Peters, Benedikt
  DE 3441129
  GB 3441129

- Stromschienensystemelement mit einem Supraleiterstrand und einem Verbindungsstück sowie Stromschiene mit einer Vielzahl von solchen Elementen
  Kudymow, Andrej; Rodriguez Zermeno, Victor; Strauß, Severin
  DE 202017102659

- Stromschienensystemelement mit einem Supraleiterstrand und einem Verbindungsstück sowie Stromschiene mit einer Vielzahl von solchen Elementen
  Kudymow, Andrej; Rodriguez Zermeno, Victor; Strauß, Severin
  EP 18720292.4

- Bitterprinzipbasierte Magnetvorrichtung und Verwendung einer bitterprinzipbasierten Magnetvorrichtung
  Arndt, Tabea
  DE 102020124852.0

- Bandleitervorrichtung und Kabel, das die Bandleitervorrichtung aufweist
  Arndt, Tabea
  DE 102020128417.9

- Hochtemperatur-Supraleitende Schaltelemente für Umrichter- und Gleichrichterschaltungen
  Martz, Simon; Noe, Mathias; Pham, Quoc Hung
  DE

Contact

Karlsruher Institute of Technology (KIT)
Institute for Technical Physics
Hermann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen

Phone: +49 721/608-direct access
E-Mail: First Name.Family Name@kit.edu

www.itep.kit.edu

Head
Prof. Dr.-Ing. Mathias Noe (-23500)
Prof. Dr. Bernhard Holzapfel (-26000)
Prof. Dr. Tabea Arndt (-23515)

Secretariat
Dagmar Klimmek (-23501)

Cryo-Engineering
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Vacuum Technology
Dr. Christian Day (-22609)

Administration
Kai Bauer (-23705)

Superconducting material development and energy applications
Prof. Dr.-Ing. Mathias Noe (-23500)
Prof. Dr. Bernhard Holzapfel (-26000)

Contact

Karlsruhe Institute of Technology (KIT)
Campus Nord
Institute for Technical Physics

Hermann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen

www.itep.kit.edu

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