Karlsruhe Institute of Technology

# ITEP – Institute for Technical Physics

Results of Research and Development
2022 Annual Report

IMPRINT

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

Phone +49 721/608-23501

www.itep.kit.edu

**TEXTS:**
Tabea Arndt, Giovanni De Carne,
Christian Day, Stefan Fink,
Thomas Giegerich, Francesco Grilli,
Jens Hänisch, Bernhard Holzapfel,
Frank Hornung, Andrej Kudymov,
Ralpf Lieztow, Ingeborg Meyer,
Mathias Noe, Stylianos Varoutis,
Klaus-Peter Weiss, Michael Wolf

**PHOTOS AND CHARTS:**
Karlsruhe Institute of Technology (KIT)

**COVER PHOTO:**
International Workshop
"HTS4fusion and MEM"
(Mechanical and Electromagnetic Properties
of Composite Superconductors)

**LAYOUT:**
modus: medien+kommunikation gmbh
www.modus-media.de

June 2023

BG-zertifiziert nach NLF / ILO-OSH 2001

# Inhalt




# Preface

**The Institute of Technical Physics (ITEP) is a national and international competence centre for fusion, superconductivity and cryotechnology with the following research fields:**

- **Superconducting and cryogenic materials**
- **Energy technology applications**
- **of superconductivity**
- **Superconducting magnet technology**
- **Fusion fuel cycle technologies.**

ITEP's work is anchored within the Helmholtz-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.

To work on these complex and mostly multidisciplinary tasks, ITEP hosts unique large-scale experimental facilities, laboratories and corresponding technical infrastructure, which is constantly adapted to changing requirements.

These include:

- Laboratory for the development of superconducting components for energy technology
- Centre for the development of superconducting materials
- Magnet laboratory for the development of specific superconducting windings and magnets
- Cryogenic high-voltage laboratory for investigating the high-voltage properties of cryogenic insulating materials
- Cryogenic materials lab to study electrical and mechanical properties at very low temperatures.

In 2022, KIT successfully appointed Prof. Giovanni de Carne to a tenure-track professorship in real-time systems in energy technology at the Institute for Technical Physics, which is an important step in the strategic anchoring of Energy Lab 2.0 work in our Institute. Unfortunately, the Institute's scientific work in 2022 continued to be hampered by Corona-related restrictions and, above all, by the strong impact of the Russian war of aggression in Ukraine. Nevertheless, our new and ongoing research projects were processed very successfully and a number of exceptional advances were made in our research fields:

Within the **research field of superconductor and cryomaterials,** an important focus is on research into new superconductors, the development of HTSL Coated conductors and the characterisation of functional materials at cryogenic temperatures. Significant progress was made in the development of complex high-entropy oxide superconductors, in the work on the ESA HTS Harness project and in the characterisation of high-temperature superconductor (HTSL) nanocomposite layers in strong magnetic fields, which was carried out in cooperation with the High Field Laboratory in Tohoku (Japan). The comprehensive set-up of the HTSL pilot-plant for Coated Conductors within the CERN collaboration was substantially completed in 2022, so that the final commissioning of the coating facility can take place in 2023.
Finally, the organisation of the combined workshop „HTS4fusion and MEM (Mechanical and Electromagtic Properties of Composite Superconductors) was an outstanding event for the entire institute in 2022. Within the framework of this international workshop with more than 70 participants from Asia, Europe and the USA, after two years of Corona abstinence, scientific discussions could finally take place again in the presence of the participants.

In the **research field of energy applications of superconductivity,** essential components for a robust and low-maintenance magnetic heater based on HTS were built and prepared for functional tests within the framework of the BMWI joint project ROWAMAG, and essential principles of superconducting switching were investigated with the help of the dynamic resistance of HTS strip conductors. The construction of a new calorimetric-based AC loss test rig significantly improves the experimental possibilities for investigating the AC losses of HTS components. The modelling of complex 3D coil structures was also successfully realised. In the area of real-time simulation of energy components, the PHIL setup could be set up with double the power and a thermal emulator could be successfully tested.

In 2022, **superconducting magnet technology** was strongly influenced by new research work on liquid hydrogen in combination with superconductivity. The coordinated joint project „AppLHy!“ has produced initial results and finalised a first version of a white paper with the partners. A general strength of the institute lies in its special expertise in combining liquid hydrogen with electrical engineering applications in a novel and efficient way. Thus, the research topic of rotating machines was also influenced by the new cooling possibilities, and new machine topologies became attractive. The research topic of superconducting magnets with robotic winding technology was able to successfully contribute to a project with the production of coils for the first time. Since there is also a trend in magnet technology towards application temperatures of 20 to 30 K (e.g. in the Collaborative Research Centre Hyperion with compact NMR magnets), the research topics here have the same focus.

In the **research field of fusion fuel cycle technologies,** ITEP is developing new processes and procedures for the internal fuel cycle of a demonstration fusion power plant (DEMO).The work for DEMO focuses on systematic technology development in the field of continuous vacuum pumping and isotope separation. For the metal foil pump, niobium has been confirmed as an alternative foil material, allowing the design phase to begin. For the mercury diffusion pump, the nozzle experiments in the HgLab were completed, so that the design can also begin here.

The production of the cryogenic pumps for the JT-60SA fusion facility was advanced significantly, so that the pumps can be delivered to Japan in **2023.** Simulations of particle removal from the divertor of the DTT fusion facility in Italy showed that the cryogenic pumps meet the requirements. Complex 3D calculations were made for the W7-X stellarator to understand what influence the cryopumps used there can have on the confinement time of the plasma. The expertise in cryovacuum technology available at ITEP was also used in a new project: the Einstein telescope. Here, a first study showed that the very demanding vacuum requirements can be mastered with cryopumps.

The training of young scientists is a very important part of our scientific work, and in 2022, in addition to 38 doctoral students, we were also able to supervise 23 Bachelor’s and Master’s theses in the faculties of physics, electrical engineering and information technology, mechanical engineering, and chemical and process engineering.
In 2022, we were able to set up new student experiments on the topics of hydrogen mobility and wind energy in the ITEP student laboratory and, despite Corona, once again welcomed five student groups and 13 interns.

Overall, 2022 was once again a very challenging year, and we would especially like to thank all of our staff most sincerely for their daily commitment to managing all of the Institute’s tasks in research, teaching and innovation, as well as all of our cooperation partners from universities, research institutions and industry for their trust and for showing understanding for the existing restrictions. We look forward to further cooperation, a scientifically equally successful year 2023 and wish you all the best!

Yours sincerely

Mathias Noe

Bernhard Holzapfel

Tabea Arndt

# Results from the Research Areas


**Set-up of the pulsed laser deposition cluster KC[4] – the KIT-CERN Cooperation on Coated Conductors**

# Superconducting- and Cryo-materials

## Coordination: Prof. Dr. Bernhard Holzapfel

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

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

### SUPERCONDUCTING MATERIALS

In the field of high-temperature superconductors, the studies on oxygen loading by X-ray diffraction (XRD) were intensified and the studies on the mixing of the rare earth *RE* in *RE*$Ba_2Cu_3O_7$ compounds were continued. Currently, XRD is mainly used at a fundamental level during the material characterisation and optimisation process to ensure phase purity and good crystallinity of REBCO thin films. However, it can be used to find out much more about the microstructure of the thin films. The goal is to integrate XRD into the characterisation process at a higher level through complete microstructure analysis. This microstructure analysis includes not only the lattice parameters and oxygen loading, but also the defect structure of the films. In this way, a link can be established between the microstructural parameters and the superconducting properties, which makes it possible to influence the superconducting properties with the help of defects such as dislocations, stacking faults and/or precipitates. In order to quantify these defects, various analytical routines and methods will be created or further developed from the literature on test samples.

The oxygen content, which is closely linked to the lattice parameters, is one of the most important microstructural properties of REBCO superconductors, as it strongly influences the critical temperature. Therefore, diffusion experiments are currently being carried out to investigate the dependence of the aforementioned lattice parameters on the oxygen content of the thin film samples. Based on the literature, the dependence of the lattice parameters on the oxygen content can be described with Vegard's law. This means that the lattice parameter c changes linearly in the orthorhombic and tetragonal phase. At the transition point from the orthorhombic to the tetragonal phase, the lattice parameters a and b equalise and c increases rapidly. This leads to the dependence of the lattice parameters shown in Figure 1, here for SmBa2Cu3O7-δ. The lattice parameter c is most affected by a change in δ and can be determined quickly and conclusively. Thus, using the data shown, it should be possible to determine the oxygen content and estimate a and b by a simple θ/2θ-scan.

Often, REBCO films are prepared with only one element on the *RE* lattice site. However, a combination of several rare earth elements on the *RE* lattice site can also have a positive effect on the superconducting properties. The main difficulty in the preparation of such layers is the optimisation of the deposition parameters, e.g. crystallisation temperature and oxygen partial pressure, as these differ for each rare earth element. In a 2022 publication, high-quality REBCO films with three and five rare-earth elements, respectively, could be produced at ITEP using chemical solution deposition [1]. Figure 2 (a) shows a chemical analysis of a sample cross-section of a (Gd,Dy,Y,Ho,Er)BCO layer near the transition to the $SrTiO_3$ substrate. The samples were analysed using scanning transmission electron microscopy (STEM) in combination with energy dispersive X-ray spectroscopy (EDXS) at the Laboratory for Electron Microscopy (LEM), yield-

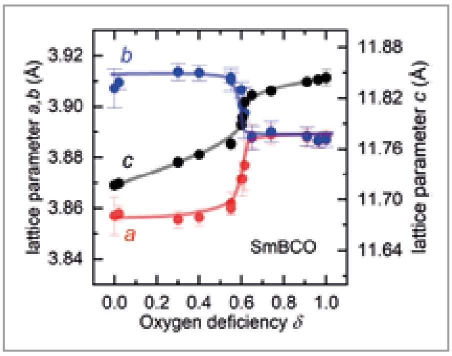



**Fig. 1: Dependence of the lattice parameters of $SmBa_2Cu_3O_{7-\delta}$ on the oxygen deficit δ.**

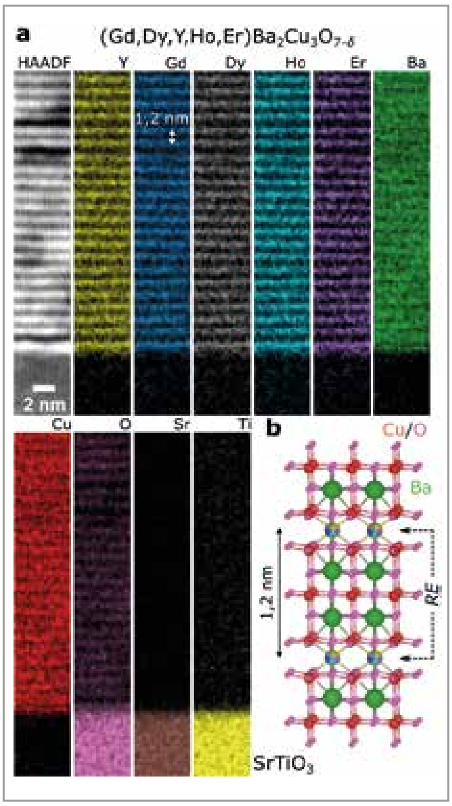



**Fig. 2: (a) STEM-EDXS elemental distribution maps and STEM-HAADF signal of a cross-sectional sample from a (Gd,Dy,Y,Ho,Er)BCO layer grown on $SrTiO_3$. (b) Model of the atomic structure. The RE planes have a vertical spacing of about 1.2 nm and are visible in (a).**

ing chemical information with high spatial resolution (< 1 nm). The differently coloured elemental distribution maps of the *RE*s show a horizontally striped structure with a vertical stripe spacing of about 1.2 nm. This spacing corresponds exactly to the lattice constant of REBCO in the vertical c-direction (see schematic of the crystal structure in Figure 2 (b). Thus, the atomic planes of the *RE*s are directly recognisable on the elemental distribution maps. The homogeneous intensity course of the *RE* signals in the element distribution maps suggests the desired homogeneous distribution of the *RE*s in the REBCO layer without the formation of local *RE* enrichments. The simultaneously recorded high-angle ring dark-field (HAADF) STEM signals directly reveal the atomic structure, since in HAADF-STEM the image intensity correlates with the average atomic number and thus heavier elements (here mainly *RE*s) appear brighter. More information on these results can also be found in the doctoral thesis by Lukas Grünewald [2].

Fluorine-free metal-organic deposition (FF-MOD) as a branch of CSD routes was further investigated during a one-year guest visit (Jiangtao Shi), as it is not only an environmentally friendly process, but also has the merit of a very high growth rate of around 100 nm/s.

In this study [3], the effects of different Y contents in YBCO on the supersaturation, crystallinity, and superconductivity of the films were investigated in the fast sintering process using the FF-MOD method. With increasing Y content, the degree of supersaturation for nucleation at the interface increases. The $Y0.8Ba_2Cu_3O_{7-\delta}+5\%Y_2O_3$ films with higher supersaturation tend to form a-axis-oriented crystals, which affect the superconductivity of the films. A lower addition of Y, i.e. $Y0.8Ba_2Cu_3O_{7-\delta}+3\%Y_2O_3$, has a positive effect on the crystallinity of the films and improves the current-carrying properties (Figure 3).

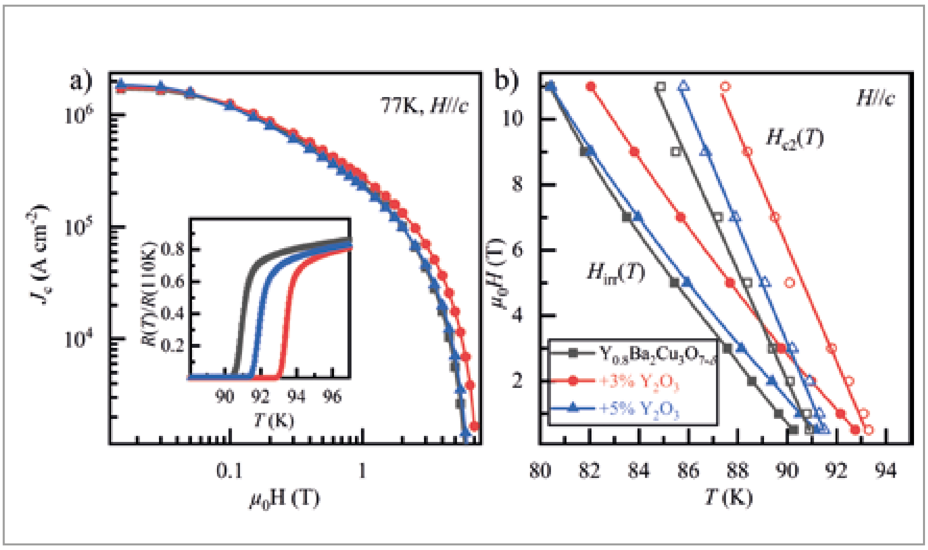



**Fig. 3: (a) critical current density, (b) phase diagram for YBCO layers of different Y content. Inset: resistive junction.**

## FE-BASED SUPERCONDUCTORS

In the field of Fe-based superconductors, a DFG project was mainly concerned with the fabrication optimisation of Fe(Se,Te) bulk samples and thin films. For laser deposition, substrate temperature, laser repetition rate, laser energy, and number of pulses were varied, and in particular, a temperature of 625 °C proved to be the optimum. In this optimisation process, various equipment improvements were made to the PLD system, which are essential for the subsequent production of high-quality films. Here, too, support was provided by a guest scientist, Jie Zhang.
In collaboration with the Institute of Physics, Chinese Academy of Science, a novel exotic vortex phase was determined on (Li,Fe) OHFeSe thin films and finally published [4]. This phase at the boundary between vortex glass and vortex liquid is reminiscent of the vortex slush phase, but in contrast only occurs in extremely pure samples.

Also completed was a study of the anisotropy of hydrogen-doped NdFeAsO films from Nagoya University, for which electrical transport data were provided. For this system, a strong dependence of the electronic anisotropy on the charge carrier density as well as a phase transition – possibly with the quantum critical point – was found at an electron density of about 4.2 $10^{21}$ $cm^{-3}$ [5].

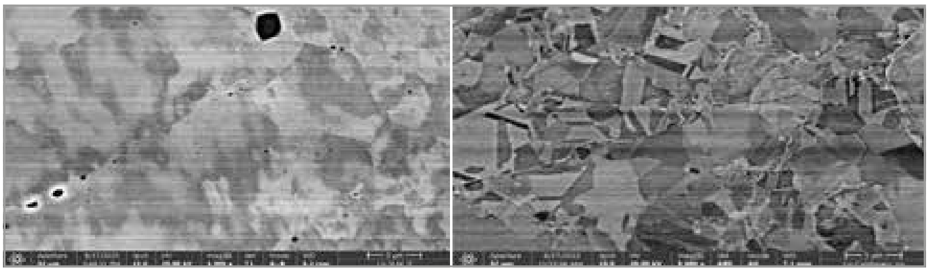

[1] P. Cayado et al., RSC Advances 12, 28831 (2022)
[2] L. Grünewald (2022) Electron Microscopic Investigation of Superconducting Fe- and Cu-based Thin Films.
[3] J. Shi et al, Applied Surface Science 612, 155820 (2023).
[4] D. Li et al, Supercond. Sci. Technol. 35 064007 (2022)
[5] M.Y. Chen et al, Phys. Rev. Mat. 6, 054802 (2022).



Contact: jens.haenisch@kit.edu


## CONDUCTOR AND CABLE TECHNOLOGIES

This research topic focuses on the development of new HTS conductor and cable architectures for specific application scenarios and their implementation in relevant conductor/cable lengths.



a) b)

**Fig. 4: Comparison between microstructure Cu-SLM (a) and Cu-Cold-Spray (b).**

### KC4: R&D PILOT LINE FOR HTS COATED CONDUCTORS

After the KIT-CERN collaboration contract KC4 was concluded at the end of 2021, the construction of the coating systems required for this could be completed in 2022 in the laboratory space provided for this purpose and the commissioning of the individual systems could begin. As part of the KC4 project, HTS Coated Conductor deposition systems, which have been developed with great success at an industrial superconductor manufacturer in recent years, will be transferred to KIT. This will make it possible in future to develop complete HTS Coated Conductor architectures for special application scenarios at ITEP and to produce them in a tape length of up to several hundred meters, so that new coil concepts can be tested, for example. With this expansion, from 2024 it will be possible for the first time at a research institute in Europe to directly link current short sample material developments with the HTS tape length requirements of application demonstrators. Within the framework of KC4, special HTS Coated Conductor architectures that are not available industrially will be developed in the coming years for the development of HTS-based accelerator magnets and their special requirement profile. Similarly, KC4 will produce wide HTS Coated Conductors that are currently not produced industrially and can be used for the development of novel coil topologies. For the HTS tape synthesis, KC4 relies on the established combination of ion beam textured buffer layers on metal substrates and their coating by pulsed laser deposition (PLD) and vapour deposition. As KC4 is an industry-independent project, it will also be possible in the medium term to provide interested research institutions and companies with an openly accessible development platform for special HTS Coated Conductor developments. In 2022, more than 500m2 of existing laboratory space at the ITEP could be rededicated to KC4 and prepared for the use of the HTS coating systems.
After delivery and installation of all planned KC4 systems, they are currently in the commissioning phase. Despite major challenges in procuring the laser gases required for pulsed laser deposition due to international supply difficulties caused by the war in Ukraine, a new laser tube was installed in the excimer laser, which is central to superconductor coating, and the excimer laser and the associated coating systems were made operational so that the first coating experiments of superconducting tapes can be realized after finalization of the optical laser guidance in Q1 2023.

Contact: bernhard.holzapfel@kit.edu

## STRUCTURAL AND FUNCTIONAL MATERIALS FOR CRYOGENIC APPLICATIONS

### PROJECT ADHYBAU

As part of the national hydrogen strategy of the Federal Republic of Germany, the Additive-Hybrid-Bauweisen (AdHyBau) project, funded by the BMWK, is creating the basis for building a hydrogen-powered electric aircraft engine. Together with the partners Siemens, MT Aerospace, Fraunhofer IWM and TU Dresden, the ITEP is carrying out fundamental cryogenic material characterisations on additively manufactured metallic materials. This enables a deeper understanding of the cryogenic material properties in the manufacturing method, e.g. Selected-Laser-Melting (SLM), Direct-Energy-Deposition (DED), or Cold-Spray (CS). Typical pores appear with these additive methods. Due to the cold spray method, copper shows a more disturbed microstructure compared to the more homogeneous SLM (Figure 4). In this context, for the use of copper as an electrical conductor, the residual resistance ratio is a parameter that must be controlled in order to optimise the design.

### PROJECT APPLHY!

The transport and application of liquid hydrogen LH2 is being investigated together with project partners via the technology platform "TransHyDE" in the BMBF lead project "AppLHy!
The behaviour of structural and functional materials under cryogenic hydrogen conditions is being investigated at ITEP and IAM-WK.
First, material conditions were defined and the material selection narrowed down. A test matrix was derived from the requirements matrix. The focus is currently on LH2 trailer containers and on superconducting cable designs of the ITEP with direct and indirect hydrogen cooling. To extend the material analyses during hydrogen exposure, a loading chamber was designed in which sample material can be exposed to hydrogen gas up to 200 °C and 200 bar in order to investigate the influence on mechanical and thermophysical properties (Figure 5a). Special hollow tensile specimens are exposed to hydrogen gas from

the inside and mechanically tested at low temperatures under static or dynamic load (Figure 5b).

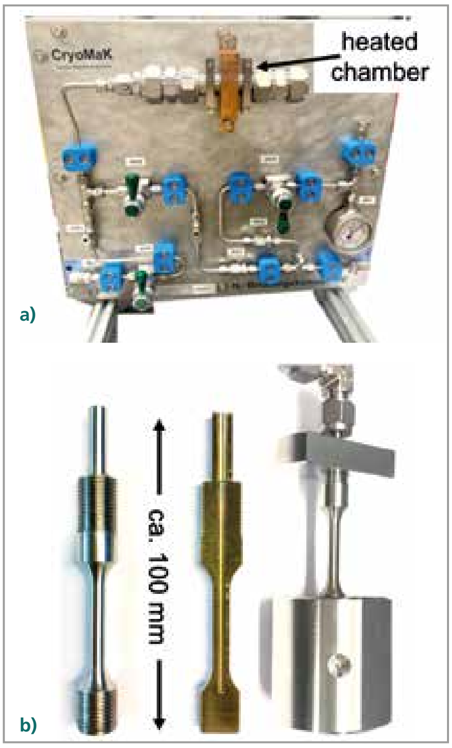



Fig. 5: H2 loading chamber (a) or H2 hollow tensile specimens (b).

## STANDARDS OF HTS CHARACTERISATION

After the successful round-robin test for tensile tests on HTS wires at cryogenic temperatures, which was coordinated by the ITEP, a proposal for a standard for such tensile tests on HTS tapes at cryogenic temperatures could be submitted to the IEC for comments.
Furthermore, the ITEP is participating in the international round-robin test for measuring the critical current under tensile stress at 77 K on an HTS wire. Four different commercially available HTS wires are characterised. In order to test the developed guideline for this type of measurement, a test set-up for the determination of the critical current as a function of the mechanical tension was adapted (Figure 6). After successful pre-tests, routine measurements are currently underway. This extends the testing possibilities of the ITEP by an essential HTS wire characterisation.

Contact: klaus.weiss@kit.edu

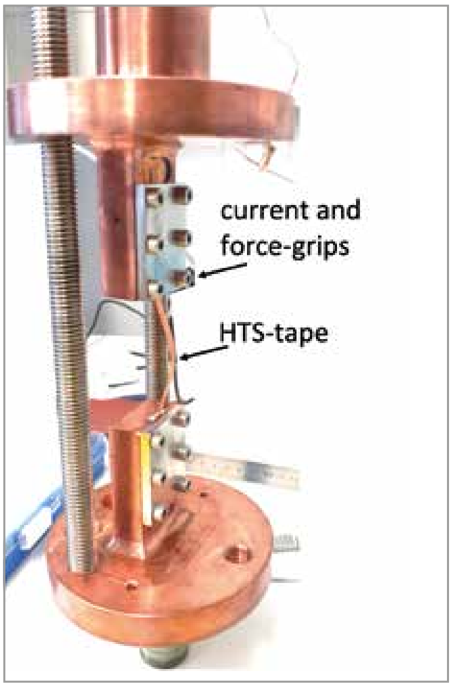



Fig. 6: Measuring device critical current under mechanical tension.

# Highlight

## Development and test of superconducting power supplies for ESA satellites

**As part of a development contract from the European Space Agency, an engineering model of an HTS cable harness for future ESA missions was developed, built and successfully tested in collaboration with CEA Grenoble and Neutron Star Systems UG, Cologne.**

As part of the European Space Agency's (ESA) Cosmic Vision and Voyage 2050 programmes, a number of satellite missions to explore the universe use extremely sensitive X-ray or infrared detectors that need to be cooled to temperatures well below 1 K. The HTS cable harness has been developed and tested successfully. To achieve the lowest temperatures in the range of 50 to 100 mK, Adiabatic Demagnetisation Coolers (ADR) are used in complex cryogenic cooling chains. The superconducting ADR magnets are usually operated on satellites with direct currents of only a few amperes due to the limited availability of electrical power. Normal conducting current feeds (SZF) from the warm to the cold would lead to too high a heat load in the cold due to the high thermal conductivity of good electrical conductors. By using superconducting SZFs, the heat load can be reduced considerably.

Within the framework of a development contract of the European Space Agency (Contract No. 4000133578/21/NL/FE, 'High Temperature Superconductor Harness for use in Cryogenic Applications'), an engineering model of an HTS power supply for future ESA missions was developed, built and subjected to various tests at ITEP.

The SZF with forward and return conductors (Figure 7) is designed for a nominal current of 2 A, but should also be able to carry a maximum current of 5 A at a temperature of 85 K at the warm end.

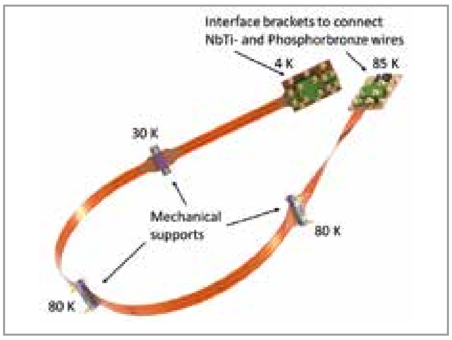



**Figure 7: CAD model of the ESA HTS power feed.**

ESA's requirements for the 1 m long cable include a flexible design that allows minimum bending radii of 50 mm in all spatial directions and at the same time withstands the strong vibrations during the rocket launch. For this, a mechanically stable cable sheath with low thermal conductivity had to be developed, which simultaneously serves as electrical insulation and protection against moisture. The specification for the maximum thermal load at the cold end with mechanical supports at 80 K and 30 K is 1 mW for the rated current of 2 A. For the forward and return conductors, 1 mm wide and 1.25 m long tapes were first cut from a 12 mm wide REBCO tape using a picosecond laser. To improve solderability, the ends were coated with Cu over a length of 125 mm. The non-copper plated areas were coated with Parylene C for moisture protection and electrical insulation. The forward and return conductors were then laminated in parallel between two 14 mm wide Kapton tapes, forming a flexible but mechanically stable sheath.

After mounting the 4-K and 85-K interfaces and the mechanical brackets, bending tests with 1000 bends up to a radius of 5 cm were carried out at the ITEP, as well as measurements of the insulation resistance. Current tests up to 20 A in LN2 (Figure 8), carried out immediately after assembly and the bending and resistance tests, showed no degradation.

In Grenoble, the HTS current leads were then subjected to an ESA-specified shaker test programme with quasi-static, sinusoidal, random and shock excitations. Again, no degradation was observed. Thermal tests are planned in Grenoble until the end of 2022. The HTS-SZF will then be returned to the ITEP for a final series of tests.

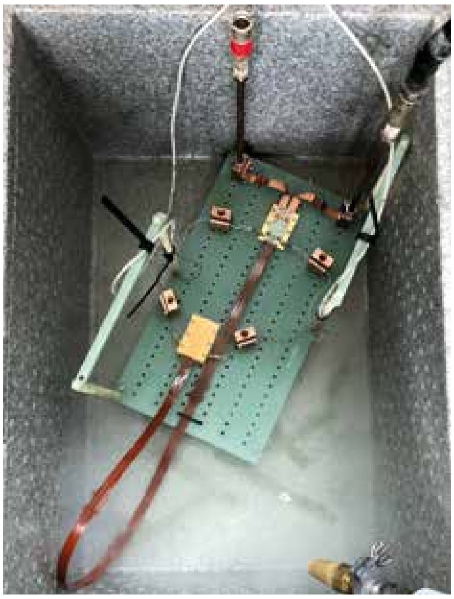


**Fig. 8: Test of the ESA HTS current lead in LN**

# Results from the Research Areas


**Power Hardware In the Loop testing hall**

# Superconducting Power Applications

**Coordination: Prof. Dr.-Ing. Mathias Noe**

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

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

The focus of the topic "Energy applications of superconductivity" is on the development of novel operating devices for electric power systems and on the development of resource- and energy-efficient applications for energy technology. In 2022, the following results were achieved:

## SUPERCONDUCTING NETWORK AND ENERGY COMPONENTS

### RESISTIVE CURRENT LIMITERS:

High-temperature superconducting current limiters have already been used successfully in the medium-voltage grid in Germany. In cooperation with TH Köln, ITEP has been commissioned by Tennet to investigate the feasibility of a resistive HTSL FCL for 380 kV, 5 kA.

An important part of the study is the high voltage technical design. First, the test voltages for different excitations were determined based on standards for comparable conventional equipment. The next step was the specification of maximum electric field strengths for the expected materials. For liquid nitrogen, experimentally derived values and properties, such as the pronounced dependence of the breakdown voltage on the loaded high-field volume, are known. However, no experimental values are available for the specified test voltages and size of the arrangement. It should also be noted that different maximum field strength values are to be derived for different voltage forms. As a high-voltage value for field calculations, 1570 kV corresponding to the cut-off lightning impulse voltage for transformers of the 380 kV grid level and a maximum field strength for bubble-free liquid nitrogen at 5 bar operating pressure (absolute value) of 3.8 kV/mm were selected. For interfaces with other materials (high-voltage bushing, support insulators) and for small high-field volumes, other maximum field strengths apply. The dimensioning of the cryogenic 380 kV bushings was carried out by comparing the cryogenically tested 230 kV bushing available at ITEP (suitable for the 110 kV grid level) with conventional 380 kV open-air oil bushings. Figure 1 shows the basic design of the superconducting current limiter (SSB). The cryostat is a cylinder with a horizontal axis and dished ends.

The feedthroughs are mounted on domes above the cylinder. Gaseous nitrogen is located below the dome cover so that conventional fastening systems can be used for the current leads. The superconducting tapes are wound in the form of bifilar coils. Depending on the tape type, different configurations result, e.g. 95 series-connected coils arranged in a cylinder shape next to each other. At the end of the cylinder, special shielding arrangements (hemisphere + cylinder + hemisphere) are mounted in the "termination" area. A reduction of the overall height is achieved by the fact that the cryogenic end of the feedthrough is located in a hole of the termination shielding arrangement. Likewise, some coils are integrated into each termination. The majority of the coils are housed outside the termination on a GFRP plate and surrounded by a shielding ring. For different transient voltage distributions between the shielding rings, different optimal shapes and distances of the shielding rings result with a fixed total length of the arrangement for all coils.

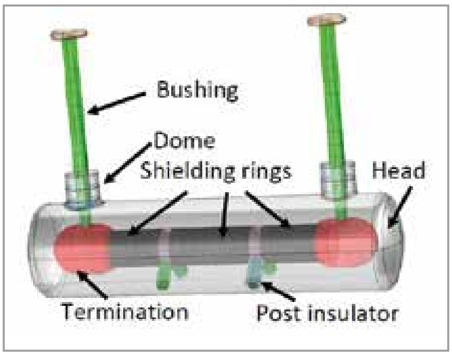



**Fig. 1 Sketch of a 380 kV superconducting current limiter for electrostatic field calculations**

The support insulators are designed in the form of bipods. Ribbed insulators experimentally show higher flashover voltages than smooth insulators. In small volumes (a few milliliters) around the top of the support insulators, overshoots of the targeted maximum field strength values along boundary layers were calculated with 3D models. Maximum field strength and volumes of exceeding the 3.8 kV / mm target value depend on the relative dielectric constant of the insulating material. To verify the calculated results, ITEP recommends an experimental test.

Contact: stefan.fink2@kit.edu

### HTS SWITCHES

A promising application for REBCO coated conductors is superconducting switching. This application is based on the dynamic resistance that occurs when the superconductor is in an alternating magnetic field. As part of a doctoral thesis, several switches were constructed and fundamentally characterized (Figure 2). To increase the resulting resistance, various normal conducting materials of the ribbon conductor were removed and tested for electrical stability and compatibility with liquid nitrogen. The next step is to build a circuit with

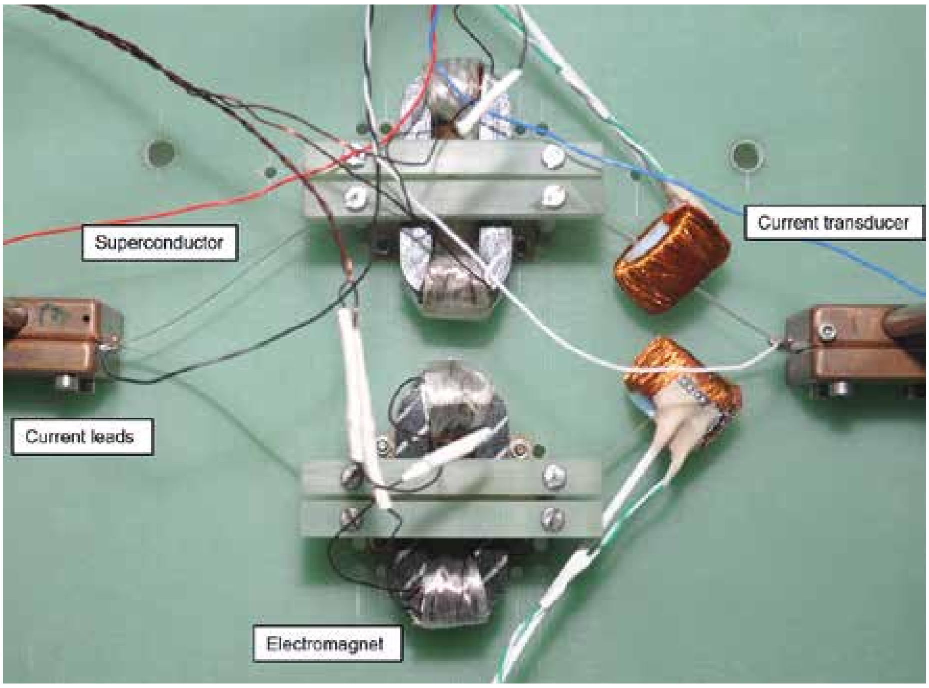



**Fig. 2: HTS circuit setup for switching characterization**

several superconducting switches.

## BMWK-PROJECT HIGHAMP

As part of the HighAmp project, subcomponents for a 20 kV cable demonstrator are being designed and tested at ITEP. The aim of the project is the replacement of existing cables in inner-city power distribution networks by systems with higher power transmission. Within the scope of the project, a demonstrator for a 3-phase HTS cable will be built. High-temperature superconductors (HTS) are used to increase the current carrying capacity. Supercooled liquid nitrogen is to be used to increase the high-voltage strength and improve cooling.
Since the start of the project on Sept. 01,.2022, a list of requirements for the cable has first been drawn up. Current carrying capacity and AC losses were calculated for two alternative HTS conductor concepts (CORC and CroCo). Based on the data, the specification for the desired HTS conductor (CORC) was prepared. A first concept for the cooling of 1 km cable length was created based on the calculated losses.
In parallel, the construction of a test stand specific to the test was started in the high voltage laboratory.

## BMWK-PROJECT DEMO200

In the framework of the DEMO200 project, a superconducting high-current system for a direct current of 200 kA is being developed.
Following the successful tests of 20 kA partial conductors in 2021, preparations were made in collaboration with the project partners Vision Electric Superconductors and Messer for testing a pressure-tight bushing and two 20 kA current supplies in pumped nitrogen. For this purpose, a cryogenic container was set up, a DC power supply for a current of 21 kA was upgraded and the first cooling processes were carried out with a dummy instead of the test specimen. The aim of the combination test planned for 2023 is to check the functionality of the individual components and to prove the temperature layer formation in the super-cooled nitrogen.

Contact: andrej.kudymow@kit.edu

## BMWK-PROJECT ROWAMAG

The essential main task of the ITEP is to develop a durable cryosystem including the cryostat and the refrigeration equipment. Together with its partners THEVA, Bültmann and Beck Maschinenfabrik, ITEP 2022 integrated the superconducting coil into the housing. The coil, the current leads and the cold bus were installed in the cooling shield (Figure 3) and then insulated against thermal radiation with MLI (multilayer insulation, Figure 4). The assembly was completed in 2022 and the magnet will be cooled to the operating temperature of 20K for the first time with the small cooler in 2023.

Contact: ralph.lietzow@kit.edu

**Fig. 3: Coil and current leads inserted into the cooling shield.**

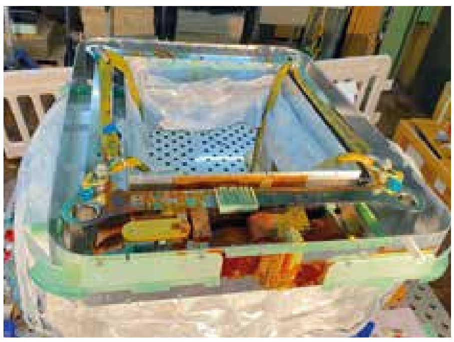


**Fig. 4: Cooling shield insulated with MLI**

## MODELLING OF SUPERCONDUCTORS AND COMPONENTS

### AC-LOSSES

A new experimental setup for measuring AC losses of high-temperature superconducting (HTS) coils was developed (Figure 5). The method consists in measuring the flow of the evaporated nitrogen related to the dissipated energy, The nitrogen gas is collected by a 3D-printed bubble collector that guides the gas into a flow sensor. A box-inside-a-box approach is used to surround the measurement chamber with a cryogenic environment. This approach allows re-directing the heat transfer from the surroundings into an intermediate zone (space between external and internal box). Since this intermediate zone operates under cryogenic temperatures, the noise and the heat transfer in the internal part of the setup are reduced.

A statistical analysis of the results based on a standard load cycle, average value, and standard deviation calculations allows assessing the variability in the measurements and expressing the results as average value and uncertainty range. The calibration and reproducibility of the measurements were verified with a set of resistors under different conditions and during different weeks. The AC transport losses in a racetrack coil for an electrical machine application were measured and compared with 3D simulation results based on a newly developed numerical model, based on the T-A formulation of Maxwell's equations. An example of such comparison is shown in Figure 6.

With the purpose of predicting the electromagnetic behavior of large coils, a finite element method-based model coupling the T-A formulation with an electrical circuit was proposed: the model presents the superconducting constituent as a global voltage parameter in the electrical circuit. This allows assessing the overall behavior of complex HTS systems involving multiple power items, while keeping a high degree of precision on the presentation of local effects.

Three-dimensional numerical simulations based on the Minimum Electro-Magnetic Entropy Production (MEMEP) method were used to predict the levitation force between a permanent magnet and a double stack of HTS tapes. The MEMEP method is much more efficient than conventional approaches based on commercial software. Figure 7 shows an example of calculated and measured levitation force as a function of the separation between the permanent magnet and the HTS double stack. The model includes the dependence of $J_c$ on the magnetic field

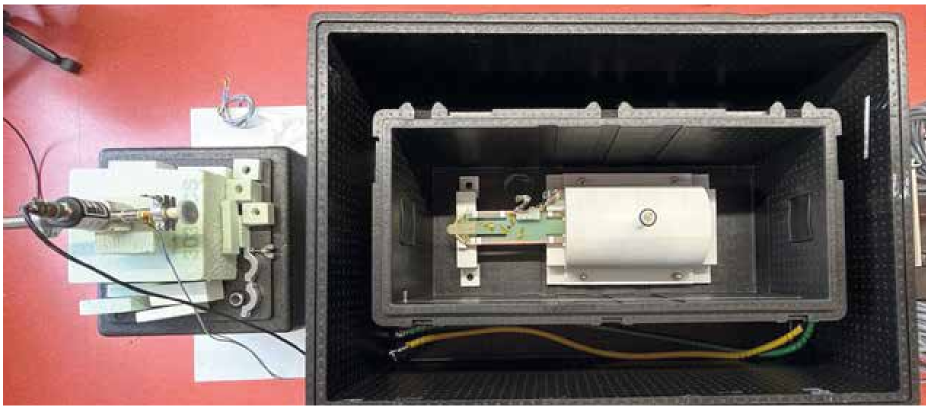


**Fig. 5. Top view of the experimental setup for measuring AC losses with calorimetric technique. One half of the HTS racetrack coil is visible in the center of the picture. The other half is covered by the white container that collects the evaporated liquid nitrogen.**

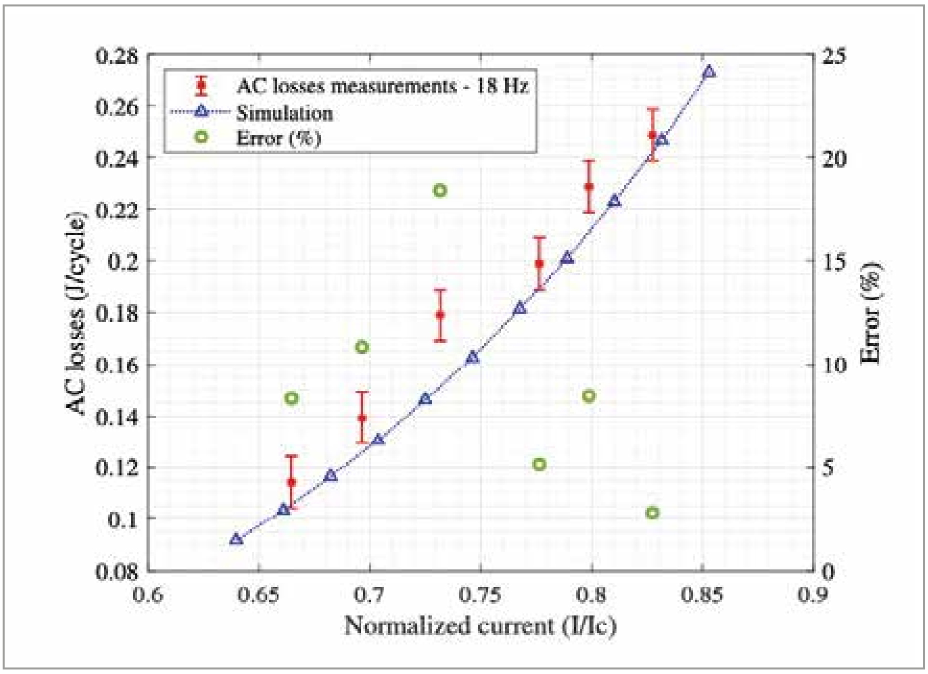



**Fig. 6: Transport AC losses of an HTS racetrack coil: comparison of simulations and measurements. The difference between measured and calculated values is evaluated on the right y-axis.**

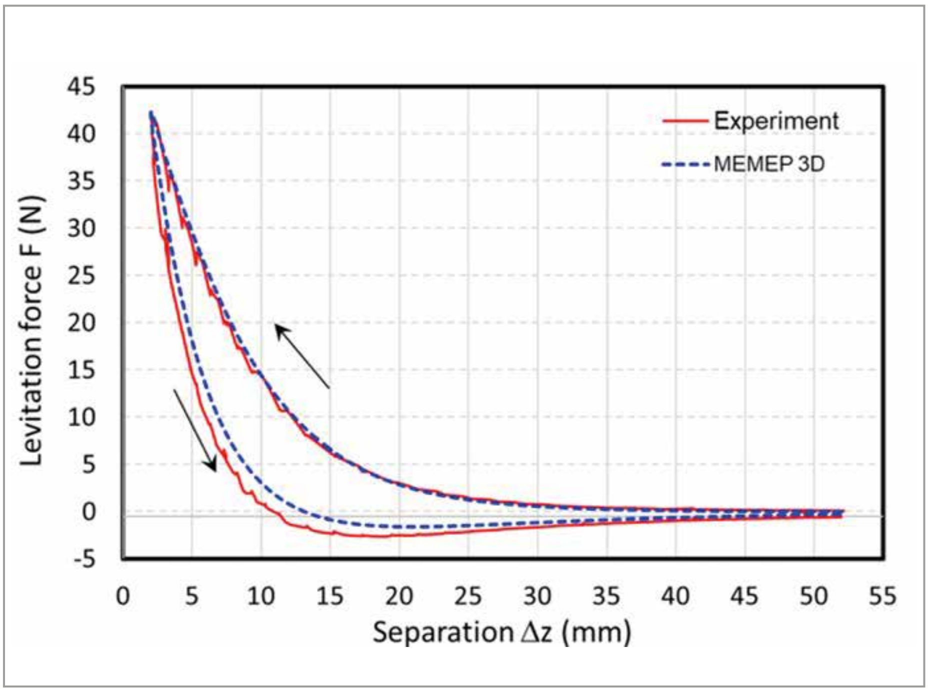



**Fig. 7: Comparison of the levitation force between a permanent magnet and a stack of HTS tapes. Results of experimental measurements (performed by evico GmbH) and simulations.**

and also its spatial non-uniformity along the tape's width. In the illustrated example, the difference between simulations and measurements is below 0.5%.

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.

To increase our experimental testing capacity, we have realized a first double-power hardware in the loop evaluation of the asynchronous grid concept, as planned in the Helmholtz Young Investigator Group "Hybrid Networks". Connecting two distribution grids, the asynchronous connection needs a realistic performance assessment from both primary and secondary side of the power electronics converter. As can be seen in Figure 8, two power amplifier groups were employed to emulate the primary and secondary grid sides (emulated in real time in a OPAL-RT simulator), and connected to a back-to-back converter of Imperix. This setup allows to test new control strategies for asynchronous grids with high fidelity and testing repeatability. In a recent publication, we were able to transform a classical distribution grid in an active prosumer, able to change actively the consumed power by means of controlled frequency variation. This enables a direct load con-

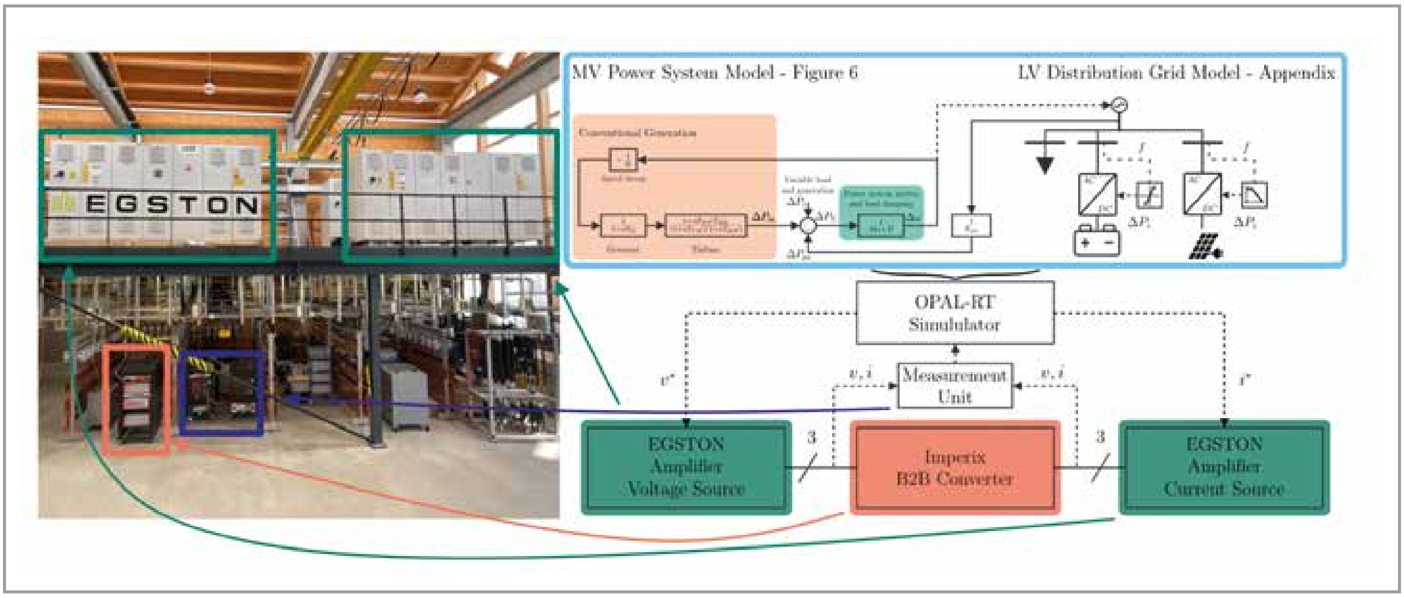



**Fig. 8: Double-power-hardware-in-the-loop setup for asynchronous grid connection**

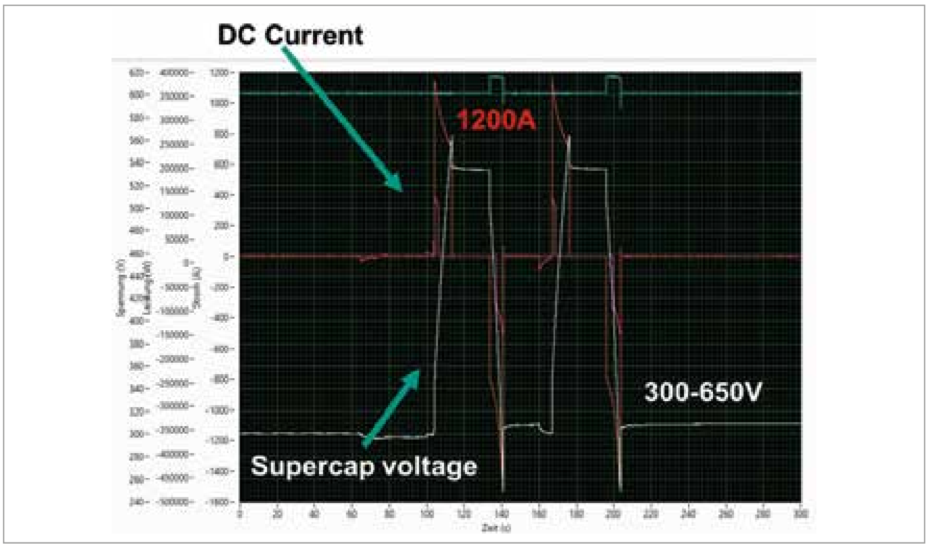



**Fig. 9: Supercapacitor Energy Storage System DC voltage (white line) and DC current (red line) during PHIL testing.**

trol, without the need for advanced communication infrastructure.

In December 2022 we have put in operation the 500kW 1.6kWh supercapacitor energy storage system, planned within the BMWi project "Flygrid". This is a joint work of ITEP and ETI, and it aims at demonstrating the potential of supercapacitors in providing ancillary services to the distribution grid, such as voltage and frequency control. Initial testing have been performed, closing the supercapacitor system in the loop for a PHIL evaluation. As can be seen in Figure 9, the supercapacitor has a fast reaction time (less than 50ms) in absorbing and injecting current (up to 1200A) and has a total energy availability at full power around 40 seconds. This kind of power / energy ration is particularly suitable for providing power quality services, such as compensating grid low voltage situations, that can last up to hundreds of milliseconds.

An important step forward in the multi-modal direction is the development and testing of a thermal emulator, that will play an important role in the multi-modal hardware in the loop concept planned in the „Hybrid Network" project. The thermal emulator (Fig. 10a) is composed is able to control the external temperature, pressure and mass flow by means of cooling and heating systems. Initial testings for understanding the best control strategy have been performed as shown in Fig. 10b. Two strategies have been proposed to control the mass flow, regulating an external pump or varying the valve opening. Due to the mechanical constraints, the first tests show that the pump perform faster and more granular control (see dotted green area in than the control through the valve.

The thermal emulator will be integrated next year with the power hardware in the loop setup, enabling the first step toward the multi-modal hardware in the loop experimental evaluation.

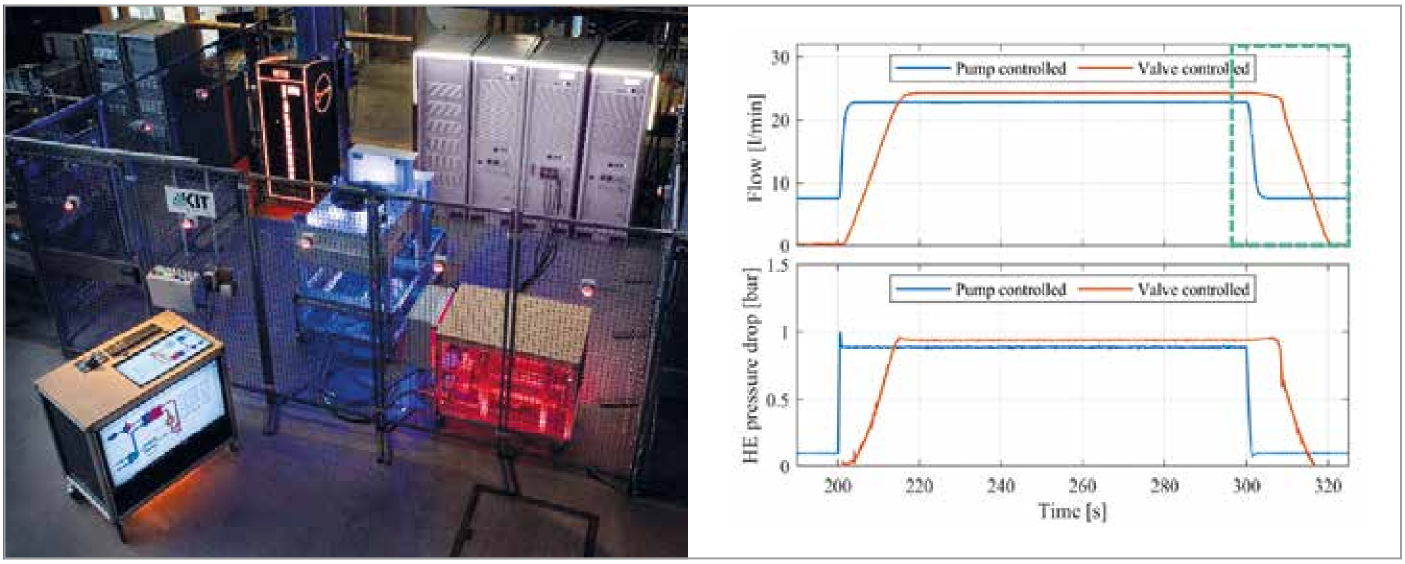



**Fig. 10: Thermal-hardware-in-the-loop: (a) experimental setup, (b) mass flow control options.**

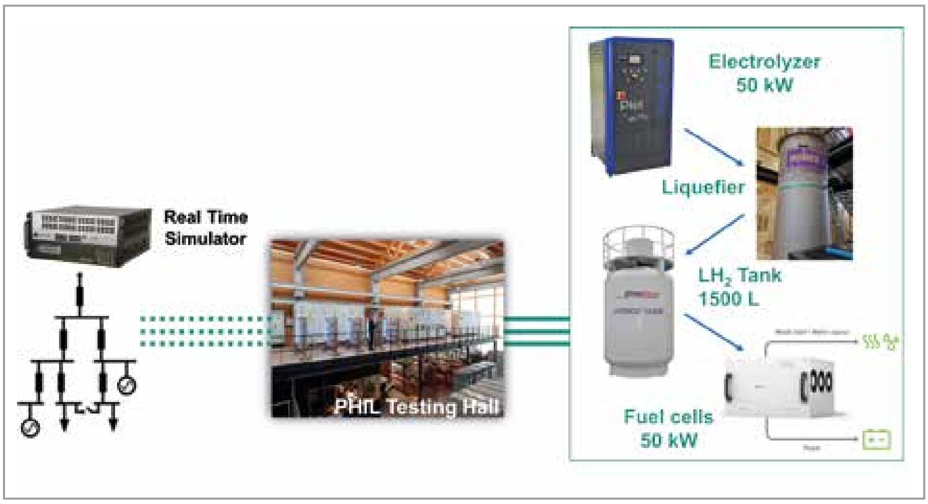



**Fig. 11: H2-in-loop lab basic schematic, from left to right: digital real time simulator, PHIL system, electrolyzer, hydrogen liquefier, liquid hydrogen storage tank, and fuel cells.**

An innovative power hardware in the loop setup is currently under construction at Energy Lab 2.0, where hydrogen-based technologies can be tested in realistic grid conditions (Fig. 11). The H2-in-loop lab consists of an alkaline elektrolyzer, a liquefying system, a liquid hydrogen storage tank and fuel cells. On the opposite of classical hydrogen experimental plants, the H2-in-loop lab will be connected with the 1MVA PHIL system, in order to reproduce experimentally the real grid conditions, where the future hydrogen energy plants will operate. In particular, the H2-in-loop lab will focus on validating their performance in providing ancillary services to the power system, in particular frequency regulation support during large disturbances.

In the SuperLink Project, a superconducting cable is expected to be twelve kilometers long and will connect a power plant at the southern location in Munich to a substation at north, which is connected to the German high-voltage transmission system (Fig. 12).
The influence of such a cable in the 110kV distribution network of Munich was investigated by ITEP. For that, four different feeding conditions were considered and

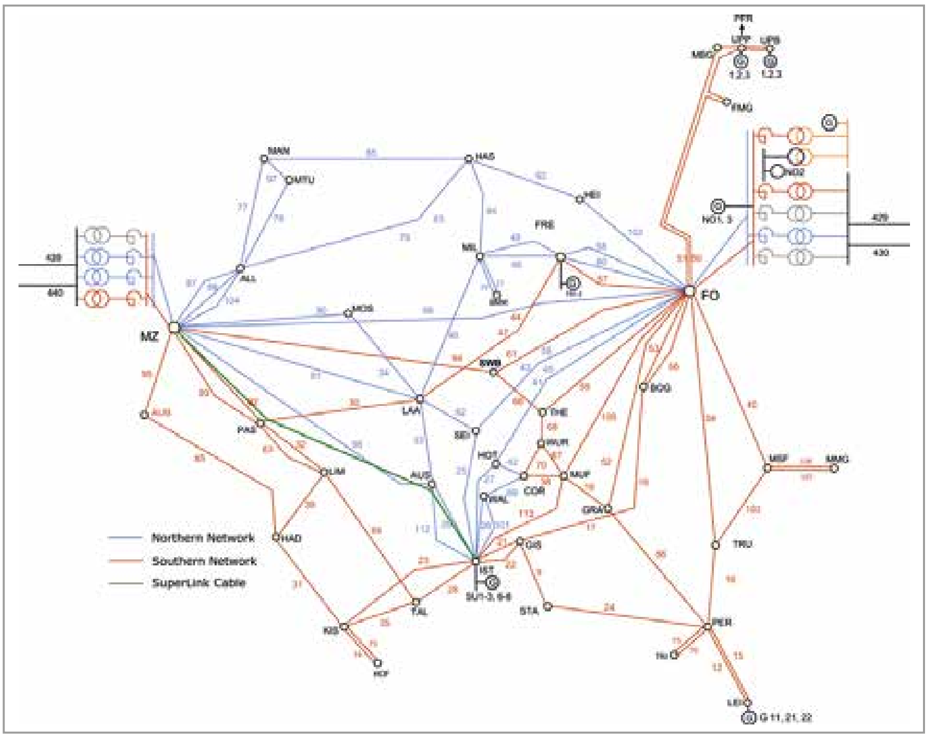



**Fig. 12: Electrical distribution network of the city of Munich with connection to long-distance transmission and planned routing of the HTS cable (green).**

three load scenarios were analyzed. The failure of the both availiable connections to the high-voltage system has been also taken into account.
In total, 66 network scenarios were studied. In general, it was concluded that the SuperLink cable can lead to the relief of overloaded cables in the network (Fig. 13(A)). Consequently, the overall losses in the network can reduced in about 15-20%. Furthermore, an important remark is the non-disturbance of the network stability. Simulations indicate that voltage levels at all the busbars of the network are not affected and no significant change on the fault current level has been identified (Fig. 13(B)).
The results of the numerical simulation also led to findings that additional simulations should be conducted for optimizations of the SWM distribution network.

Contact: giovanni.carne@kit.edu
sousa@kit.edu for Supralink project

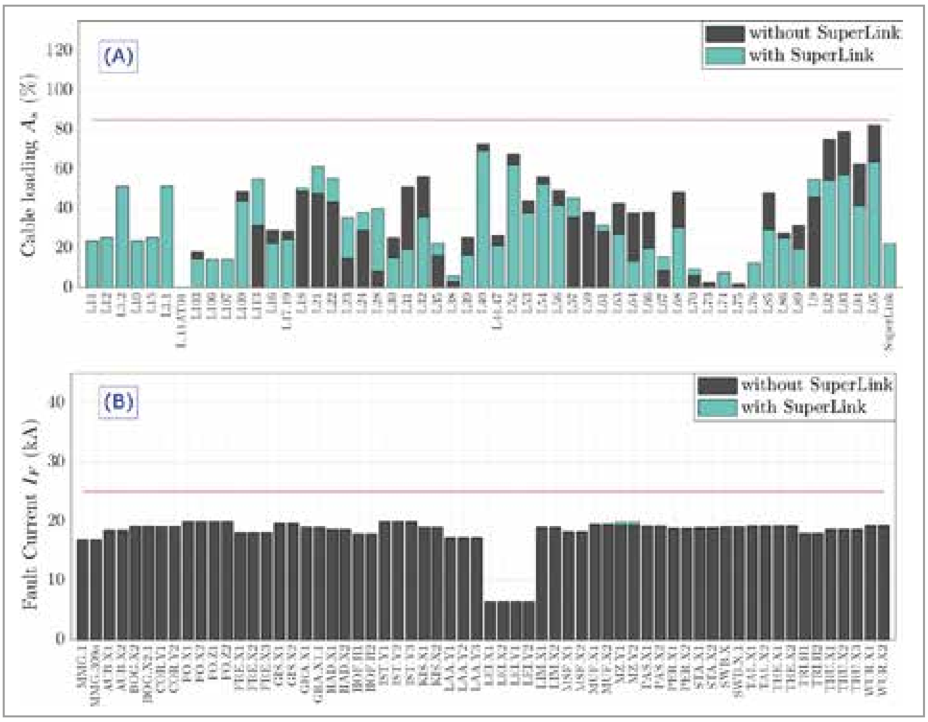



**Fig. 13: (A) Influence of the SuperLink cable on the current loading of all other lines in the 110 kV network and (B) Short circuit levels on each bus-bar before and after the intallation of the Super-Link cable.**

# Results from the Research Areas


**View from the computer control station (monitor with camera system in the lower half of the image) into the robot cell during the winding process of HTS coils with great precision for the MEESST project (several research fields and topics involved) with the participation of all three robots (part-process). The robotic winding allows easy, controlled readjustment by experts to compensate for material imperfections.**

# Superconducting Magnet Technology

**Coordination: Prof. Dr. Tabea Arndt**

In 2022, this research field was enhanced by special collaboration within the individual research groups. In this way, the specific expertise of the research areas could be used in a coordinated manner in projects and for know-how exchange.

In 2022, the three research topics "Coil and Magnet Technology", "High-Current Components for Hydrogen Technologies and Fusion" and "Rotating Machines" have been involved in the activities of the SupraGenSys project, MEESST project ApLHy! project and cross-institute work (Bachelor's thesis on HTS -Gyrotron magnets, PhD thesis on accelerator magnets).
A particular success, made possible by the participation of many KIT institutes and external partners, was the acquisition of the "Hyperion" collaborative research centre for the development of miniaturized HTS magnets for special applications in NMR technology. In Hyperion, the research fields of superconducting and cryogenic materials and superconducting magnet technology work together, particularly in project A01. Below is the logo representing the Collaborative Research Centre.

SFB 1527 HyPERiON

## COIL AND MAGNET TECHNOLOGY

### ROBOTIC WINDING TECHNOLOGY

Applications with superconducting coils require increasingly complex, truly three-dimensional winding geometries. These can no longer be easily manufactured by hand and the usual winding machines. To fulfil this need, a self-designed robotic winding system was built in 2020 and 2021. The coil body is held and oriented by a rotatable and pivoting work piece positioner. Two non-collaborative robots wind the superconductor wire. The wire is fed by a so-called winding hand, which picks up the supply spool and keeps the wire tension at the set value via a servo motor and tension sensor. For maximum flexibility in wire guidance, the two robots can pass the winding hand to each other and guide it alternately. The winding trajectory, i.e. the actual winding process, is programmed and simulated in advance with a digital twin of the robot cell.
In 2022, among other things, the following details in the robot cell were refined: (1) For perfect winding, it is essential that the cell is precisely measured, i.e. the relative positions of the robots, the positioning table and other tools and shelves are known exactly. To ensure this, the cell was calibrated with a laser triangulation system to an accuracy of approx. ±0.2 mm. With this system, the cell can be recalibrated at any time, e.g. in the event of any modifications. (2) The tension is regulated via a specifically programmed PID control. The parameters have been optimised to reduce peaks in the tension which shows that the changing geometry (winding radius or lever arm) and the mass of the superconductor supply as the supply coil is unwound (approx. a factor of three) have a significant influence on the PID parameters. (3) When winding in automatic mode, nobody is allowed to be in the winding cell. To check the winding pattern of the wire, a corresponding camera system was installed.
With the cell optimized in this way, a first disc-shaped pancake winding with 40 turns of HTS superconducting wire was built. One of the robots which was mounted on the work piece positioner circled the coil body with its winding hand and wound the ribbon-shaped wire in layers. The coil was then cast with epoxy resin in the vacuum pressure impregnation system (VPI) (see the following section and Figure 1).

**Fig. 1: Impregnated HTS Pancake-Winding (right) with impregnation mould.**

### COOLING CONCEPT: THERMOSIPHON WITH CRYO-COOLER

Due to the relatively high critical temperature of the HTS, cooling with liquid helium, which is extremely expensive, is not required in power engineering applications. Instead, dry cooling with cryo-coolers is recommended. Usually these are coupled to the object to be cooled with solid copper and its thermal energy is dissipated via heat conduction. More innovative and with higher heat transfer is the use of thermosiphons (heat pipes). A thermosiphon consists of a tube, an evaporator and a condenser and contains a small amount of a cryogen, in this case neon. The object to be cooled and the cold head of the cryo-cooler are connected to each other via the thermosiphon. The liquefied cryogen vaporizes on the object and flows to the condenser, where it liquefies again. The mass flow and the phase transitions result in an extremely effective heat dissipation.
The construction of a test stand for the fundamental investigation of this cooling technology progressed in 2022. After the design and manufacture of the mechanical parts in 2021, the electrical supply of the system has

**Fig. 2: Operation (left) and control cabinet (under construction, right) of the heat pipe test stand.**

now begun. A comprehensive control cabinet with components for controlling the pumps, heaters, etc. and recording measured variables - such as temperatures and pressures - is currently under construction (see Figure 2).
Commissioning of the plant and initial tests are planned for 2023.

### 30 K-TEST PLATFORM

With the increasing demand for superconducting components comes the need to test them. For this purpose, construction of an appropriate test platform began in 2022. With this facility, it will be possible to investigate larger (approx. 1.5 m x 1 m) current-loaded superconducting components without a background field at temperatures of 30 K and higher with currents of up to 3000 A. The cooling takes place cryogenically by means of three cryo-coolers; two for the power leads and one for the component under test.
In 2022, the system's cryostat was installed in the hole and construction of the necessary infrastructure began. The electrical supply for the laboratory space was installed along with the cooling water supply. In 2023, the construction of the test stand will be completed and will be ready for operation. Figure 3 shows the state of construction by the end of 2022.

### MEESST

As part of the EU project MEESST ("Magnetohydrodynamic Enhanced Entry System for Space Transportation"), a magnet was de-

**Fig. 3: State of construction of the 30 K test platform at the end of 2022.**

signed and manufactured at ITEP to be used for experiments in the plasma channels of the Institute for Space Systems at the University of Stuttgart and the Von Karmann Institute in Brussels. The MEESST magnet consists of 5 individual, non-insulated pancake coils (PCS, Figure 4), cooled to a temperature of 30 K via conduction cooling.

Due to the limited length of the conductors supplied by Theva, different types of contacts had to be designed and qualified:

- Connection of two conductors within a pancake coil
- Connection of two pancake coils, inner
- Connection of two pancake coils, outer
- Connections of the power supply to the two outer pancake coils.

The contact resistances for bridge connections of the 4 mm wide REBCO strip conductors measured on short samples in LN2 were in the range of 90 – 175 nΩ, so that the losses to be expected in the magnet at a current of 100 A are in the order of 1-2 mW per bridge contact.

In November 2022 the MEESST magnet was wound using the robots installed at ITEP (Figure 5).
The spatial distribution of the maximum magnetic field expected at I~Ic was calculated using angle-dependent Ic(B,T) data and is shown in Figure 6. A field of about 5.5 T is reached at the inner windings of the magnet. On the surface of the probe body, the magnetic field reaches a value of around 2 T at maximum current.

Alongside the production of the magnet, a data acquisition system was set up and the control of the magnet was programmed. Magnet tests in the VATESTA facility are

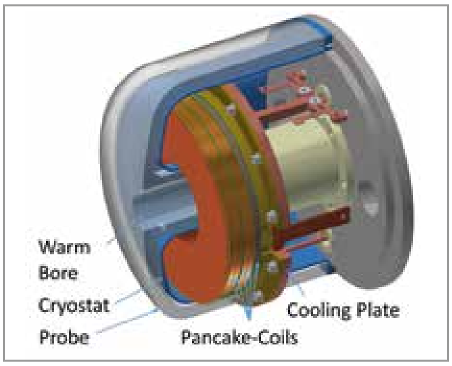



**Fig. 4: MEESST HTS-Magnet with cryostat and probe body.**

planned for 12/2022 and 01/2023, following which the magnet will be delivered to the project partner Absolut Systems (Grenoble), where it will be installed in the cryostat and test body. The first plasma experiments are planned for Q2/2023.

Contact: frank.hornung@kit.edu

**Fig. 5: Robotic winding of the MEESST HTS-Magnets.**

## HIGH CURRENT COMPONENTS FOR HYDROGEN AND FUSION

In the research area high-current components for hydrogen and fusion, EUROfusion is working on HTS high-current conductors for future fusion magnets and within the TransHyDE project AppLHy! various topics related to the transport and application of liquid hydrogen were studied.

### QUENCH STUDIES ON HTS HIGH-CURRENT CONDUCTORS FOR FUSION MAGNETS

In 2022, progress was made on the production of a high-temperature supercon-

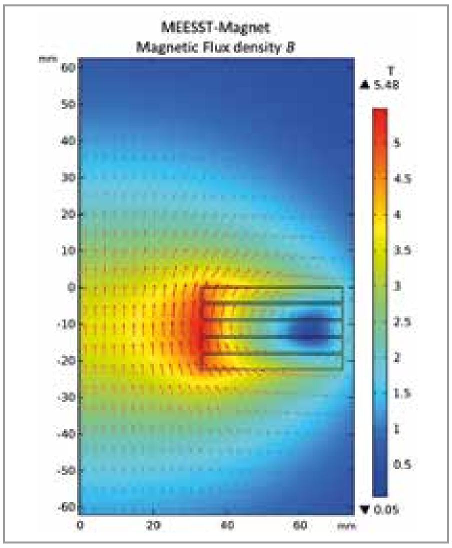



**Fig. 6: Calculated magnetic flux density |B| of the MEESST-Magneten at $I \approx I_c$ (T=30 K).**

ducting (HTS) high-current sample for investigating quench behaviour, along with many other components required for this that were still to be developed. The geometry of the conductor in question consists of three stranded superconducting elements in a steel housing. Supercritical helium flows through cooling channels inside the sample and thus cools it. In the planned experiment, temperatures of the individual elements (superconductor, helium, steel housing) and electrical voltages along the sample must be measured with spatial and time resolution. The following is an overview of some of the work completed in 2022.

## VACUUM FEED FOR OPTICAL TEMPERATURE SENSORS

Optical temperature sensors are provided for measuring temperatures inside the high-current HTS quench probe, for which a vacuum-tight feed through is required for use on the test object itself and for calibrating the fibre. The feed through implemented is shown in Fig. 7 and consists of six single feeds in a DN 100 ISO-K flange. Each fibre runs inside a resin-filled stainless steel tube that is tightly connected to the flange.

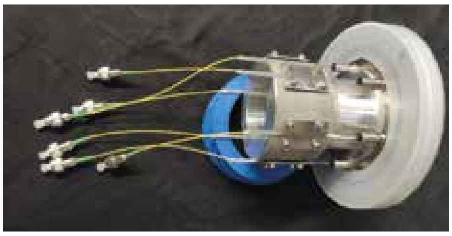


**Fig. 7: Vacuum feed through for optical temperature sensors**

## CONSTRUCTION OF MEASUREMENT ELECTRONICS FOR THE ACCEPTANCE TEST

For the final acceptance test of the probe, a new measurement system was required that can record the high channel density of the SULTAN probe and process the different sensor types used. For this purpose, a mobile measurement system was designed and set up in a 19-inch rack (Fig. 8). The rack contains a computer with a data acquisition module for measuring the voltage at the resistance temperature sensors and the superconducting cable itself. The supply current for the temperature sensors is provided by two precision current sources. A measuring system dedicated to the optical temperature sensors communicates via a LAN connection with the measuring computer, which records all measurement data. A patch box with D-Sub plug contacts was set up for acceptance tests and the measurement operation itself, which can also be used later for other measurements with a high channel density. The new measurement electronics have already been used successfully to calibrate the optical temperature sensors from 0–125 °C for the welding work on the sample housing and to monitor the temperature during welding.

## HOUSING WELDING

The welding work on the sample housing was completed by the end of 2022. After the superconductors were placed in the housing half-shells and the second half-shell was pressed on and attached, the optical fibres for temperature measurement were threaded in and in this way the temperature was monitored during welding. Both sample legs were welded simultaneously so that one leg could always cool down, effectively limiting the temperature. To complete the sample, the electrical connections will be sealed at the beginning of next year, sensors will be attached and the sample will be mounted in its retaining bracket.

**Fig. 8: Mobile measuring rack for the acceptance test of the quench sample**

## APPLHY! – TRANSPORT AND APPLICATION OF LIQUID HYDROGEN

The work on liquid hydrogen is part of the BMBF’s TransHyDE lead hydrogen project. Here the ITEP coordinates the work of the AppLHy! partnership on the transport and use of liquid hydrogen and is involved in all work packages of the joint project. In 2022, the group jointly wrote a white paper on liquid hydrogen, which will be published in early 2023.

Within the project, a hydrogen liquefaction plant is being implemented at KIT in which gaseous hydrogen (GH2) is taken from a tank and cooled to the condensation temperature in several steps in heat exchangers. Liquid nitrogen (LN2) is used to cool the hydrogen from room temperature (300 K) to 80 K. A helium low-temperature system is available for further cooling of the hydrogen from 80 K to approx. 17 K. The cryogenic hydrogen mass flow is then expanded and liquefied in a liquid hydrogen tank with a Joule-Thompson valve. From there it can be transferred to mobile liquid hydrogen transport containers and transported to experiments. In addition to hydrogen liquefaction and filling in transport cans, the transport of liquid hydrogen through a demonstration pipeline with a superconducting cable is also being investigated. For this, the mass flow of hydrogen, which has been cooled from the vacuum container with heat exchangers, can alternatively be expanded into a pump cryostat and from there supply the pipeline with liquid hydrogen. Fig. 9 shows a greatly simplified process diagram of the hydrogen liquefaction plant. A detailed piping and instrument flow diagram was drawn up in 2022 and the dimensions of the main components were defined. On this basis, an installation planning draft was developed, which is currently being coordinated.

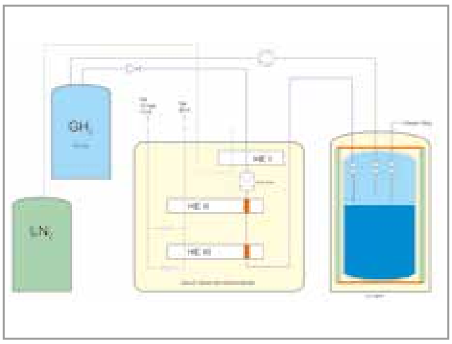



Fig. 9: Highly simplified process diagram of the hydrogen liquefaction plant

Two doctoral theses started this year study the combined liquid hydrogen and electrical energy transport in a joint hybrid energy transmission pipeline. Initially, a comparison was made between different regions of Germany and Europe with regard to existing and planned gas and electricity networks as well as energy flows, and the Brunsbüttel / Hamburg region was identified as an attractive environment for detailed study.
Fig. 10 shows a map of the Brunsbüttel / Hamburg region with existing and planned pipeline networks as well as the diagram of a hybrid energy transmission pipeline.
In a second study, different conductor arrangements and geometries were considered and compared with regard to the planned experimental demonstration of the concept. In order to assess whether the electrical line must be in direct contact with the flowing hydrogen or whether a separate arrangement – and the associated weaker, indirect cooling – is sufficient, experimental investigations in liquid nitrogen were carried out on the thermal coupling of the electrical line.

Fig. 11 shows a schematic and photo of the experimental setup, with a piece of cable separated from the vessel walls by spacers. The gap was filled with helium gas at different pressures and the steady-state temperatures of the cable were determined at different heating powers. The results (Fig. 11 graph) agree well with empirical expectations for helium pressures that are not too low over the entire heating power range studied and have been incorporated into a detailed cable design and decision-making process for the line arrangement to be tested in the demonstrator.

More results of research work from the AppLHy! can be found in the research areas Structural and Functional Materials for Cryo Applications and Rotating Machines.

Contact: michael.wolf@kit.edu

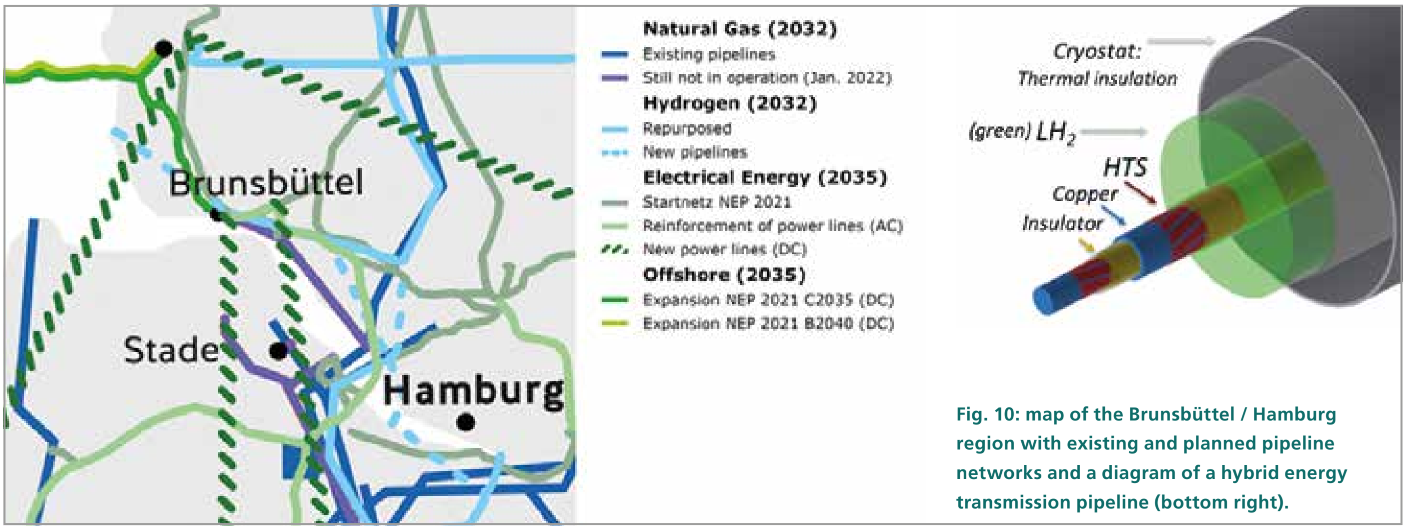



Fig. 10: map of the Brunsbüttel / Hamburg region with existing and planned pipeline networks and a diagram of a hybrid energy transmission pipeline (bottom right).

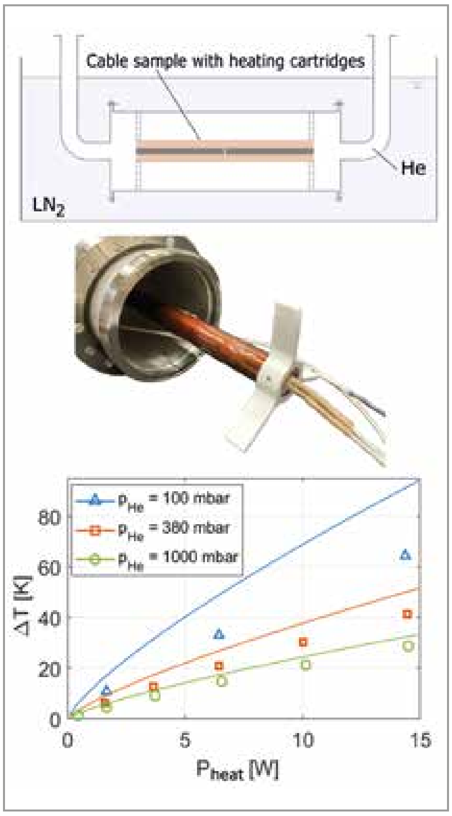



**Fig. 11: Scheme (top) and photo (middle) of the experimental setup for investigating the indirect thermal coupling of the electrical line and experimental results (bottom).**

## ROTATING MACHINES

### TEST STANDS FOR HTS-ROTORS

The HTS Geno Test Rig project was approved as part of a strategic development investment by the HGF for a period of 4 years with a budget of around 3.8 million euros. The aim of the project is to set up a test stand for the development of rotating, superconducting motors and generators. (Fig. 12)

The HTS coils are to be cooled down to 30 K with the help of a thermosiphon circuit with neon, operated with an excitation current of approx. 3 kA and with a rotation speed of up to 1000 rpm. In 2022, work continued on adapting the infrastructure (requirements for the electrical supply, the refrigeration system, lighting). The cryo-coolers have arrived and the rail system is laid. A comprehensive specification of the vacuum container has been created. Work has been carried out on a new design for the rotor body and on various physical measurement techniques. Due to the enormous price increases of basic materials by up to 300%, the reduced availability of components and the very long delivery times, unforeseen external difficulties arise, which may lead to adaptive measures in 2023.

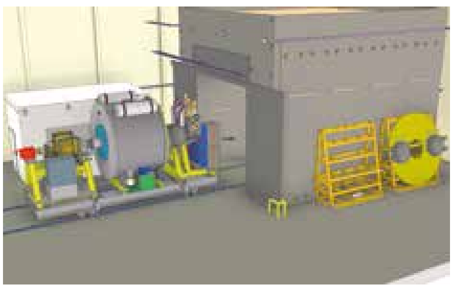


**Fig. 12: Sketch of the HTS-Geno test rig.**

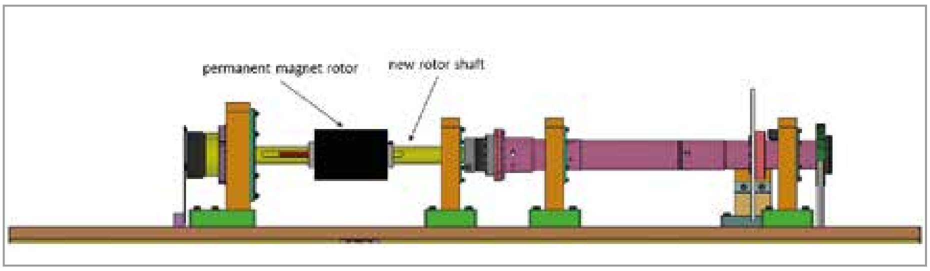



**Fig.13: Drawing of the rotation test stand including new shaft and rotor**

Furthermore, a rotation test stand for the characterization of non-planar superconducting coils is under construction at ITEP. The basis of the rotation test stand is the scaffolding that was made available to our institute as part of a cooperation with Rolls-Royce Germany Ltd & Co KG. During the course of the year, more components of the rotation test stand were prepared for the installation and the drive of the rotor. The basis for the speed-variable drive of the rotor is an asynchronous machine controlled by a frequency converter with a rated output of 4 kW, which can accelerate the rotor to speeds of up to 1000 rpm. The electrical structure and the wiring of the drive have already been completed and are waiting for the installation of the new rotor together with the shaft (Figure 13).

Contact: tabea.arndt@kit.edu;
mathias.noe@kit.edu

### SUPERCONDUCTING GENERATORS FOR WIND ENERGY

A conceptual design for a cryogenic cooling system for a fully superconducting 10 MW generator for wind turbines was developed for the BMWi project SupraGenSys. In a first step, different versions were compared with each other in terms of balance. A design was chosen in which both the stator and the rotor have an operating temperature of 30 K and completely dispense with an intercooled thermal shield. The rotor coils are kept at the right temperature by means of rotating small coolers and a line-cooled connection. Due to the increased heat input from the AC losses of the stator coils, a cooling design with forced helium gas cooling was investigated. The finite element calculations show that the temperature margin of 30 K can be maintained at a helium inlet temperature of 28 K, a static helium pressure of 20 bar and mass flow rates above 6.3 g/s.

Figure 14 shows the temperature profile in the cross-section of the coil heatsink and the helium gas channel with a diameter of 10 mm.

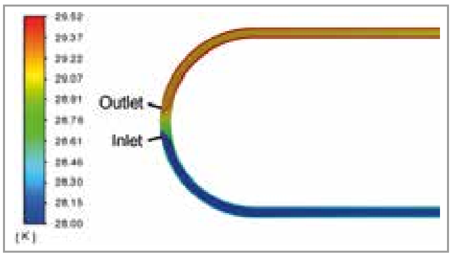



**Fig. 14: Temperature profile in the cross section of the coil body and helium gas channel.**

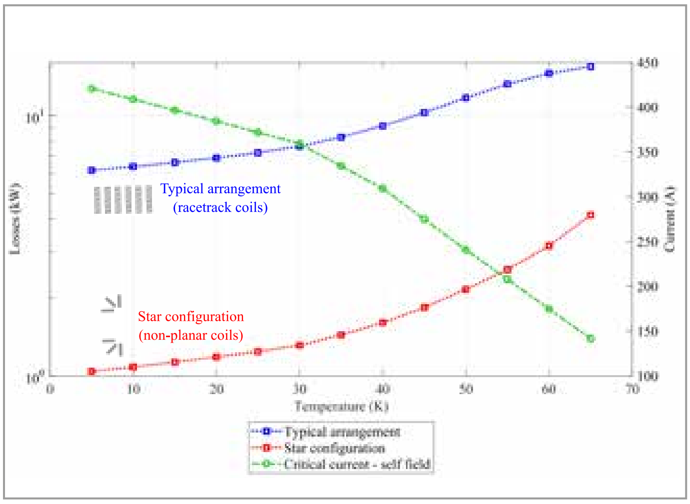



Fig. 15: Comparison of the losses in the stator winding of a superconducting generator

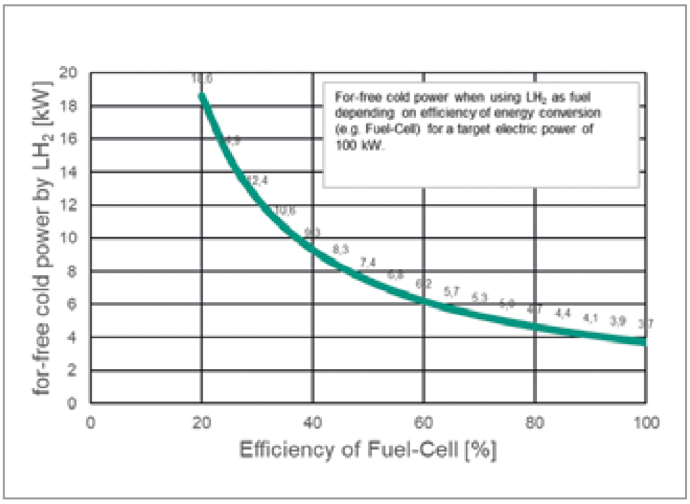



Fig. 17: „Cooling capacity" of the liquid hydrogen corresponding to the efficiency of a fuel cell.

In order to reduce the AC losses in the superconducting winding of a generator for a wind turbine, a new arrangement of the stator coils was proposed. This is based on aligning the coils with the magnetic field and achieves a 73 % reduction in AC losses in the stator coils. Figure 15 shows a comparison of the losses in the stator winding of a superconducting generator in the typical configuration (racetrack coils) and in the proposed arrangement (star configuration, non-planar coils).

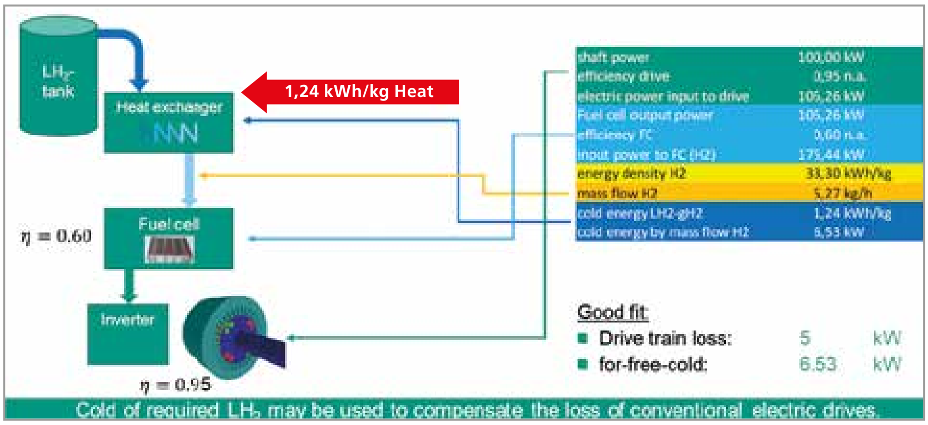
This graph also shows the self-field behaviour of the critical current of the strip as the temperature drops. The loss reduction achieved with the star configuration at 65 K cannot be achieved with the conventional racetrack coils, even if the critical current of the tape is doubled or the operating temperature of the coils is reduced to 5 K in the typical configuration. A system for measuring AC transport losses in superconducting coils for wind turbine applications was designed and built. Two racetrack coils have already been measured and the results are in good agreement with a new modelling approach developed to study coils with complex geometries and based on the 3D homogenization of the T-A formulation. These results support and encourage the development of non-planar coils for electrical machine applications that enable significant reductions in AC losses.

Contact: francesco.grilli@kit.edu

## POWER TRANSMISSION IN CONNECTION WITH LIQUID HYDROGEN ($LH_2$)

Within the research topic "High current components for Hydrogen and Fusion" new topologies for fully superconducting motors (rotor and stator windings with HTS) were investigated. The DUDA concept with air-gap winding (with iron only to guide the external magnetic flux) offers new options, especially for compact, high-performance machines. The cooling provided by the $LH_2$ allows for a particularly advantageous use of the DUDA concept by the easy dissipation of the heat from the high number of (resistive) contacts. The power transmissions of different vehicle types based on $LH_2$ as fuel and a fuel cell for electrical power generation were analysed. Figure 16 shows the basic structure of such a drive.
Figure 17 makes it clear that the level of the provided "free cooling capacity" depends on the efficiency of the fuel cell: the lower the efficiency of the electrical energy generation in the fuel cell, the more (initially cold) fuel $LH_2$ has to be supplied.

In the overall system, it is clear that almost 6 percentage points in efficiency can be achieved




| | |
|---|---|
| shaft power | 100,00 kW |
| efficiency drive | 0,95 n.a. |
| electric power input to drive | 105,26 kW |
| Fuel cell output power | 105,26 kW |
| efficiency FC | 0,60 n.a. |
| input power to FC (H2) | 175,44 kW |
| energy density H2 | 33,30 kWh/kg |
| mass flow H2 | 5,27 kg/h |
| cold energy LH2-gH2 | 1,24 kWh/kg |
| cold energy by mass flow H2 | 6,53 kW |

Fig. 16: Fuel cell electric drive train using liquid hydrogen as the fuel
Tab.1 (right): Power flows in a fuel cell electric powertrain and liquid hydrogen "cooling power" for a mechanical power of 100 kW

# Highlight
## Whitepaper on Liquid Hydrogen

A particular success is the finalisation of the white paper after around twelve months of content-related and coordinating work. This important document will be published via the BMBF in early 2023.

In the document, the authors of all 13 project partners involved address the fields of application in the energy system, the properties of liquid hydrogen, safety and materials, liquefaction and storage, transport options, use in stationary and mobile applications and, of course, the combination of liquid hydrogen and superconductivity. With many caveats and outdated information still circulating in many areas (e.g. liquefaction, storage and safety), this document is an important step towards a timely assessment of the potential of liquid hydrogen. Detailed updates are also expected as the work progresses.

# Results from the Research Areas

**Retained mercury dew during active experimental operation with the NEMESIS setup in the HgLab Karlsruhe.**

# 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 utilised. The research field covers all three key technologies of the fuel cycle: matter injection, vacuum technology and tritium processing 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 anchored in the European Fusion Programme via the EUROfusion consortium, which will develop a concept design of the DEMO demonstration fusion power plant by 2027.

## 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. The work also covers vacuum technologies for other large-scale fusion facilities, such as the European neutron source IFMIF-DONES or the fusion reactors 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 of the JT-60SA tokamak in Japan, which, after an extended commissioning phase, will go into operation in 2023. After an initial experimental campaign, the machine will then be reopened and completed with further installations. This includes a powerful cryogenic pump system (nine identical cryopumps), which will be integrated directly into the divertor ring.

**Fig. 1: Components of the JT-60SA Cryopumps.**

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. The production of the pumps progressed very well during the reporting period, so that delivery to Japan can be expected in the first half of 2023.

The design of the cryopump follows the proven cryosorption pump concept developed at the Institute. Figure 1 illustrates some manufactured components from the different manufacturing phases.

The upper figure shows hydroformed structures during the pressure test. The

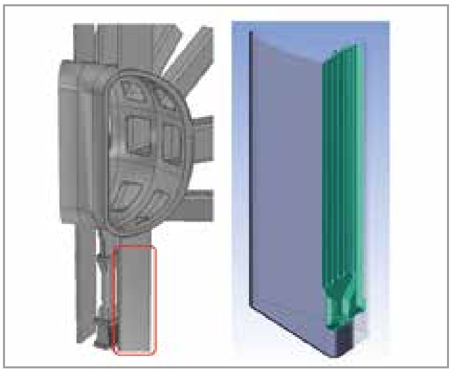


**Fig. 2: The DTT vacuum vessel with the pumping ducts (red) to house the vacuum systems (green).**

middle figure presents a 4 K panel, first untreated, then coated with activated carbon, fitted with resistance heaters and temperature sensors. The lower image shows the blackened chevron baffles during the dimensional inspection test.

Another focus of our 2022 work was the development of DTT's vacuum systems, a new fusion machine in Italy. DTT is to develop and demonstrate the divertor solution for DEMO's; operation, however, will be only without tritium. Based on the studies we conducted in 2021, it was decided to also use customised cryosorption cryopumps for DTT. In 2022, we therefore developed a pump design for the lower vertical ducts, see Figure 2. Space is very limited, which is a particular challenge. We finally decided to suspend the cryopump on the wide side of the trapezoidal cross-section over a length of about 2 m, which is an optimised design point in terms of pumping probability and heat load.

The Institute's Vacuum Technology Division is also involved in the Einstein Telescope

(ET). The Einstein Telescope is a design concept for a third-generation European gravitational wave detector that will be about 10 times more sensitive than today's instruments (LIGO, Virgo). ET will consist of three nested detectors, each consisting of two Michelsen interferometers with 10-kilometre-long arms and a tube width of the order of 1 m. One of these interferometers will measure low-frequency gravitational waves (2 to 40 Hertz), while the other will be tuned to higher-frequency gravitational waves. The Einstein Telescope will be one of the largest ultra-high vacuum systems in the world.

The improvement in sensitivity to gravitational waves expected to be achieved by ET is partly due to the fact that the pressure in the beam tubes will be much lower than in previous systems (10-10 mbar total pressure with partial pressures for water below 10-12 mbar and for heavy components below 10-14 mbar). A further improvement in the low-frequency range is essentially due to a cryogenically cooled detector mirror. During the reporting period, the essential vacuum requirements for this spectrometer were compiled and an initial concept was drawn up showing where cryogenic pumps must be installed at low temperature (between 3.5 and 10 K, depending on the technology chosen, to pump hydrogen) and where cryogenic

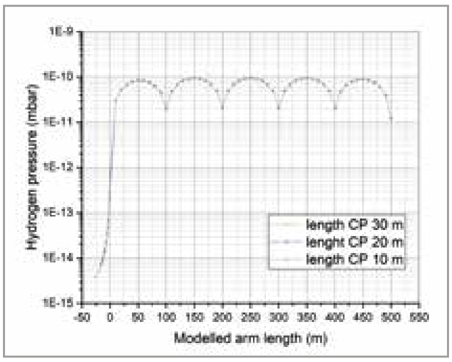



**Fig. 3: Calculated pressure profile in the transition between beam pipe and cryogenic mirror oft he low frequency interferometer.**

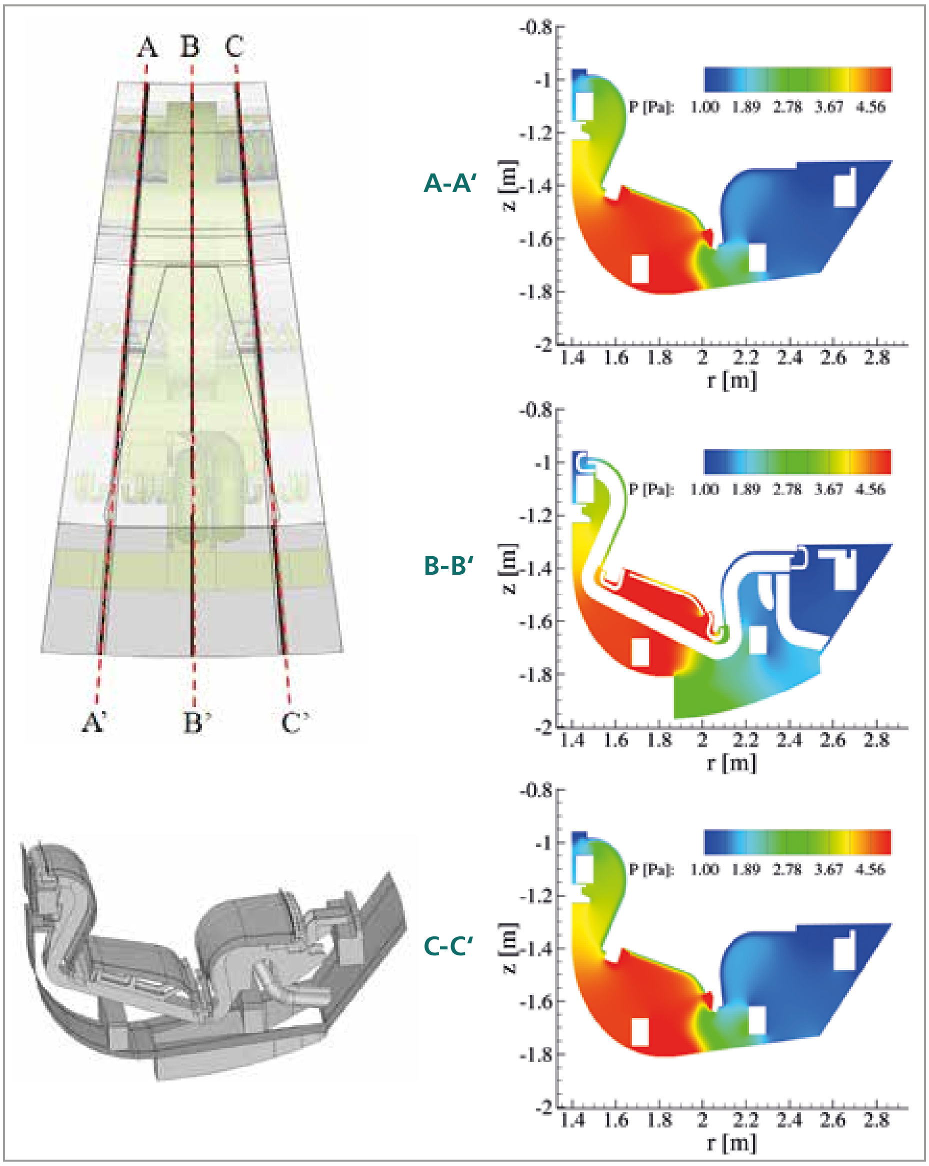



**Fig.4: Illustration of the calculated pressure profiles in different sectional cuts of the DTT divertor.**

pumps at 80 K are sufficient (to pump essentially water). Gas particles impinging on the cryogenic mirror must be eliminated as much as possible, as they increase the background. Condensable species such as water must also be pumped out effectively so as not to negatively affect the optical properties of the mirror. With the developed concept, measurement times of the order of 1 year are possible. Figure 3 shows a typical pressure curve along the jet pipe. In this example, vacuum pumping stations are installed every 100 m. At position 0 the cryogenic pump ends, the cryogenic mirror is located at -30m. A cryogenic pump is assumed in front of the mirror, the length of which has been varied here. It can be seen that the length has no significant influence on the hydrogen profile, from which it can be concluded that it is sufficient to operate the cryogenic pump at 80K and thus without pumping speed for hydrogen.

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. This is done in a very accurate manner by solving the Boltzmann equation, which describes the flow in the entire range of rarefaction. However, the solution of this equation for realistic applications (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 was achieved in the acceleration of the DIVGAS Boltzmann solving code developed at the Institute. This made it possible in 2022 to calculate complicated divertor geometries in 3D for the very first time. This was demonstrated for the two machines DTT and the W7-X stellarator.

For DTT, it was possible to quantify the particle flows and pressure profiles to be pumped for the geometry of the first test divertor. Figure 4 shows an example of the pressure distribution in the area below the divertor when it is pumped by cryopumps.

The analysis also showed that the poloidal gaps between the individual divertor cassettes (10 mm nominal) cause a deterioration of the pumping behaviour of about 10%, while the toroidal gaps between the divertor cassette and the vessel wall can deteriorate the effective pumping speed by up to 60%. While there is mechanically no headroom to reduce the poloidal tolerances, consideration is now being given to at least partially closing the toroidal gaps.

The divertor of W7X has also been analysed. This is done in view of the fact that the current pumping system with turbo-

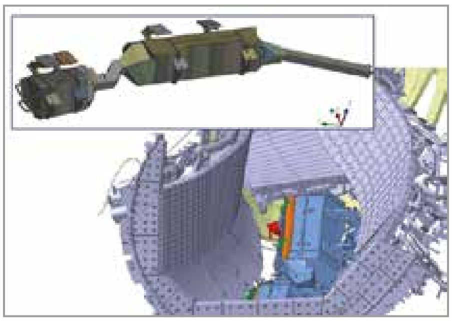


**Fig. 5: View of the new W7-X cryopumps below the divertor targets.**

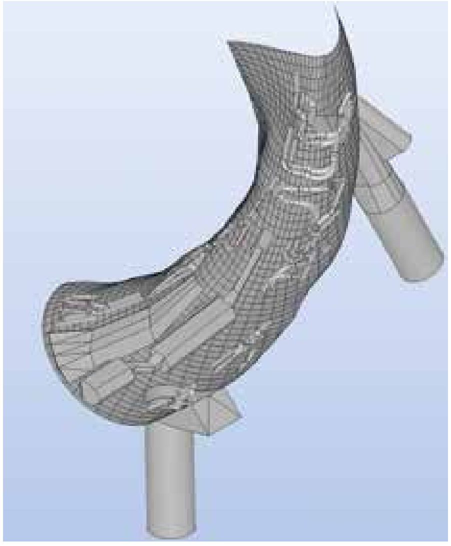


**Fig. 6: Final 3D Model of the sub-divertor with pumps and interconnection piping.**

molecular pumps will be replaced by cryopumps, see Figure 5. The final model is shown in Figure 6.

Contact: stylianos.varoutis@kit.edu

## VACUUM HYDRAULICS AND HYDROGEN SEPARATION

The research topic "Vacuum Hydraulics and Hydrogen Separation" addresses the the flow behaviour of fluids, especially liquid metals, in machines and processes under vacuum. Accordingly, the 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. One 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 vacuum and roughing pumps.

In metal foil pump development, the first measurements were made on vanadium as a foil material during the reporting period. Compared to niobium, the material used so far, the pumping results were only slightly worse. Also, no isotope effect could be detected, which is very desirable. Fig. 7 shows the plasma-driven permeation flux density through the vanadium foil for the two cases before and after decarbonisation of the foil. . During this treatment, carbon located in the sub-surface region is released as CO, which improves the diffusivity of oxygen in the material. This is a desirable effect to maintain the stability of the surface condition and thus the permeation process. It can be seen that – before decarbonisation – a higher foil temperature can improve the post-transport of oxygen to the surface and thus the stability of the permeation flux, but that it still decreases with the duration of plasma exposure. Only with the removal of the carbon the superpermeability of the foil is resistant to the exposure to energetic particles of the plasma. In order to further improve the long-term stability of the process with respect to energetic plasma particles, the direct line of sight of plasma and foil will be provided with a screen currently being investigated in a further series of tests.

Downstream of the metal foil pump, linear mercury diffusion pumps are to be used, possibly in combination with ejector pumps.

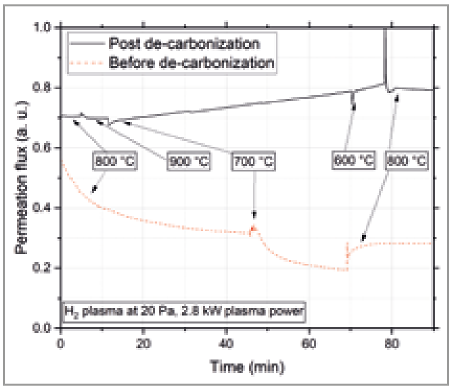



**Fig. 7: Influence of de-carbonization on permeation fluxes.**

Fig. 8: NEMESIS experimental setup for characterising nozzle geometries for mercury diffusion pumps.

Fig. 9: Multi-channel gas mix- and gas analysing system for the DIPAK gas supply infrastructure.

Fig. 10: Control boxes for connecting flange heating and temperature sensors tot eh DIPAK test vessel.

The working principle of diffusion pumps is based on the transfer of momentum from mercury vapour, which is accelerated to supersonic velocity in nozzles, to the gas particles to be pumped. For a better understanding of the flow processes in the nozzle, experiments were carried out in 2022 on the new experimental setup NEMESIS, see Fig. 8.

The measured pressures can be used to validate the developed flow code.

The development work underway in this research topic qualifies new and innovative processes for application in the DEMO fuel cycle as part of the systematic technology development undertaken at the Institute. In the next 3 years, all new technology developments carried out at the institute (metal foil pump, mercury vacuum pumps, temperature swing process for hydrogen separation) will lead to prototype maturity.
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 supply of material via pellet injection. This requires a separate test environment. After a planning and application phase lasting several years, the DIPAK project (Direct Internal Recycling Integrated Development Platform Karlsruhe) was approved by all sides (Presidium, Senate and Supervisory Board KIT, EUROfusion, Helmholtz Energy Programme) in 2021. However, as a result of the current economic world situation with problems in supply chains and the procurability of raw materials, major cost increases have occurred in the meantime, which now have to be replanned. This applies to both the construction and manufacture of the large test vessel that will simulate the torus of a future fusion power plant.

In preparation for DIPAK, work has already begun on building the scientific infrastructure. Figure 9 shows a new gas mixing and analysis facility. It will make it possible to produce the gas mixtures needed continuously for the experiments fully automatically and accurately.

For the test vessel, which must be able to be heated to 200°C, the infrastructure close to the vessel was prepared and integrated into the process control system (Siemens PCS7). In addition to the distributors and measuring points for the thermo oil-based heating system, this also includes the four control boxes for connecting the approx. 200 temperature sensors and flange heaters (Figure 10).

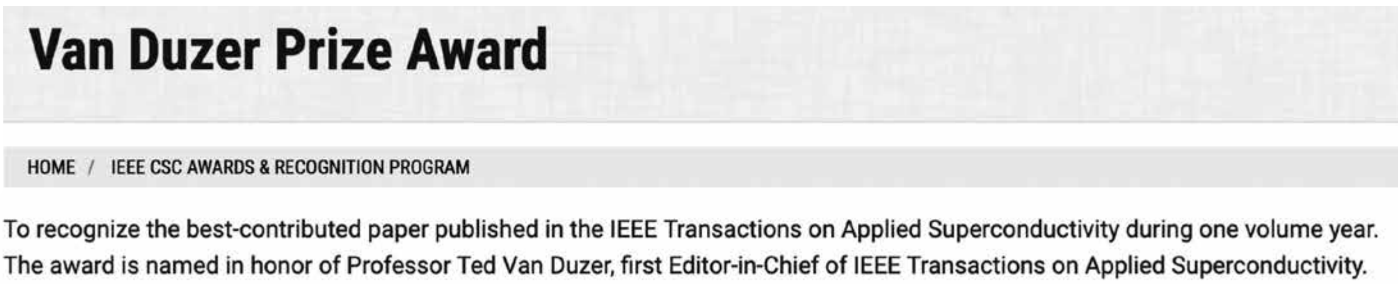
Contact: thomas.giegerich@kit.edu

# Prizes and awards

In 2022, the following awards and prizes were presented for the work and to the employees of ITEP.

Giovanni De Carne has been appointed to a tenure-track professorship for "Real-time Systems in Energy Technology" at the KIT Faculty of Electrical Engineering and Information Technology as of 7 November 2022. He has headed the Helmholtz junior research group "Real-time systems in energy technology" at the ITEP since 2020.

Jonas Schwenzer, doctoral student, was awarded the second prize in the student paper competition at the Fusion Technology Conference (TOFE) of the American Nuclear Society in June 2022 for his modelling work on tritium recovery from the coolant of the helium-cooled pebble bed blanket. His transient simulations revealed significant optimization potentials of the reference process.

## Van Duzer Prize Award

HOME / IEEE CSC AWARDS & RECOGNITION PROGRAM

To recognize the best-contributed paper published in the IEEE Transactions on Applied Superconductivity during one volume year. The award is named in honor of Professor Ted Van Duzer, first Editor-in-Chief of IEEE Transactions on Applied Superconductivity.

**Topology Comparison of Superconducting AC Machines for Hybrid Electric Aircraft**
Matthias Corduan, Martin Boll, Roman Bause, Marijn P. Oomen, Mykhaylo Filipenko , and Mathias Noe
https://ieeexplore.ieee.org/document/8947911

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. Cristian Gleason González

**Modelling and validation of neutral particle flow by means of stochastic algorithms using the example of a fusion divertor**

Particle exhaust is a key process that controls the plasma core density and the pumping of the helium ash resulting from the nuclear reactions. In fusion machines such as the tokamak in its divertor configuration, the particle flow in the divertor and sub-divertor region is related to the pressure and the gas being pumped by the torus pumping system. This is why predictive modelling of the neutral particle exhaust is crucial for understanding and optimizing the operation of vacuum systems in fusion devices.

The main objective of this dissertation is to develop a numerical tool based on the Direct Simulation Monte Carlo (DSMC) Method that describes the neutral gas flow in fusion applications. Within the framework of the open-source C++ toolbox for computational fluid dynamics OpenFOAM, the in-built DSMC solver dsmcFoam is employed for modelling, simulation and validation of the neutral gas flows in the divertor region for the first time in a context of nuclear fusion.

A necessary step to apply dsmcFoam in the divertor region is to first assure that the solver can predict gas flows in a simple geometry. Therefore, dsmcFoam is verified against theoretical predictions and benchmarked against independent numerical calculations. The sensitivity analysis on the modelling parameters shows the effect on the flow field as a function of time step, cell size dependence and number of modelled particles. As second step, the solver capabilities are further developed in order to model gas absorption at surfaces via the sticking probability.

With this new capability of the dsmcFoam solver, the analysis of the particle exhaust in the sub-divertor of the JT-60SA tokamak is performed. The analysis has been carried out by studying the gas flow with and without neutral particle interactions.

The study confirms that the inclusion of the intermolecular collisions plays a significant role in the description of the neutral gas transport and the gas flow development in tokamak sub-divertors. This is reflected in the pressure values of the DSMC collisional model, which increase by around 25% and 40% when comparing them with the pressure values obtained with the DSMC collisionless model. The comparison is the first of its type in the application context of nuclear fusion.

The second application of dsmcFoam consists of the analysis of the gas flow of a high-divertor pressure scenario in ITER tokamak. For a 10 Pa divertor pressure, the neutral gas flow in the ITER 2009-design geometry is studied. Here the gas recirculation effects through the divertor are shown to have a direct dependency with the pressure at the pumping port. The relation between the gas flowing towards the plasma main chamber and the pressure at the pumping port is obtained.

The simulations have shown that the pressure increase at the pumping port enhances the gas flow at the low-field side, whereas at the high-field side no effect is observed. The study shows that flow reversal near the pumping port occurs, leading to an increase of the particle flow at the low-field side.

The combination of experimental data and DSMC modelling allows the calculation of neutral gas flow in the entire sub-divertor of ASDEX Upgrade (AUG) tokamak. With the installed Divertor III in AUG, dedicated experiments focusing in the particle exhaust by operating the tokamak with full cryogenic pumping is modelled with DSMC. The modelling shows that particle fluxes below the divertor dome region and at the low-field side are comparable to the experimental measurements. A mismatch is found between the calculated gas fluxes in the modelling and the measurements at the high-field side manometers, behind the divertor target. The sensitivities on the AUG modelling have shed light onto dependencies among sub-divertor parameters, which are of relevance in the divertor operation

# Dr. Yannick Hörstensmeyer

**Holistic fuel cycle modelling of a future fusion reactor**

The fuel cycle of a fusion power plant is a complex chemical plant that essentially provides the hydrogen isotopes deuterium and tritium for fusion. Since a large part of this gas mixture leaves the fusion reactor without fusing, the cycle ensures that the hydrogen can be recovered with high efficiency from the resulting exhaust gas stream. To do this, the process gas must first be transferred out of the reactor by means of vacuum pumps. Then the hydrogen is filtered out of the exhaust gas mixture via various separation processes. Finally, the hydrogen mixture is fed back into the reactor.

This thesis represents the first systematic work to derive the function and structure of the inner fuel cycle for the DEMO demonstration fusion power plant from its boundary conditions. Then the relevant physical relationships of the technologies used are described and integrated into a simulation programme as independent models. Special focus is placed on the physical interactions of hydrogen (separately for all six isotopologues) with itself, liquids such as water (in all forms of tritiation) and various metals, which form the basis of the separation processes used.
To integrate all subsystems, the simulation programme maps the complete cycle transiently in the commercial software ASPEN® Custom Modeler. In this way, the behaviour at the operating point, during the start-up process and for variable boundary conditions can be modelled.

The model for the fuel cycle describes all systems – arranged in three interconnected loops - in a self-consistent manner. In this way, an initial dimensioning of the technologies used is worked out in the work.

In the innermost loop, the throughputs were essentially obtained via scale-ups of current experimental results. The assumed total throughput of 450 Pa m³/s is processed by 26 metal foil pumps, which extract 80% of the hydrogen in pure form and recycle it directly. The vacuum pumping system comprises 15 linear diffusion pumps and over 100 liquid ring pumps. The recycled gas fraction is then mixed with the reflux from the other circuits of the fuel cycle and fed into the plasma. Cryogenic pellet injectors are mainly used for this.

In the next loop, the hydrogen is separated again, here with membranes. A two-stage permeator is provided for this purpose, which already separates 99.5% of the hydrogen in the first stage with 45 units. The composition of the hydrogen is then adjusted in a temperature change process.

In the outer loop, the remaining hydrogen stream is finally separated into the pure isotopes via cryogenic distillation. Produced tritiated water is separated electrolytically and purified in scrubbers in a mass transfer process. The outer circuit is where the tritium produced and extracted by the tritium blankets is imported.

Using a representative reference point, an optimisation of the fuel cycle is carried out according to its main design criteria. From the consideration of the entire system under the conditions of the assumed operating point of the plant, an estimated tritium loss term of 1.6 g per year results, which is related to an operational tritium inventory of 6.3 kg. The individual contributions to the total tritium inventory are derived and are largely found in liquid form or in solid beds.

Using mass balances, the influence of each subsystem on the reference point is discussed, taking into account the loss terms. In a parameter study, the most important boundary conditions of the fuel cycle are then varied and corresponding adaptation possibilities of the system are described. The result of this work is a comprehensive, modular and well-founded tool for optimising future fuel cycles.

This work will be continued in a follow-up work.

# Dr. Cyra Neugebauer

**Investigation on the Semi-Continuous Separation of Hydrogen Isotopes for Fusion**

The fuel cycle is of central importance for the efficient operation of a fusion power plant. During the fuel feed, the required particle ratio of the two hydrogen isotopes deuterium and tritium must be precisely maintained in the specified injection mass flow and the proportion of impurities must not exceed certain upper limits. In the past (e.g. ITER), the hydrogen fraction in the exhaust gas was separated into the individual isotopes by means of cryogenic distillation only. Since the reactor is operated with a large fuel surplus, very large flows must be processed for this purpose, which already leads to large tritium inventories at ITER. A scale-up of the ITER approach to the size of a demonstration fusion power plant (DEMO) would lead to unacceptable tritium inventories of between 15 and 20 kg. On the one hand, this is problematic because the stocks of tritium, for which there is no significant natural source, are limited. Secondly, tritium is a radioactivity source and therefore the maximum permissible release in a fusion power plant is only one gram per year. ITER has an inventory of about 4 kg, and the goal is to be able to comply with this limit for a fusion power plant as well.

For this reason, a new architecture of the fuel cycle has been proposed, which distributes the separation task between two systems. For this purpose, a semi-continuous temperature change process is to be connected upstream of the cryogenic distillation, which effects a pre-separation. In the separation process, a partial stream with a composition of D and T that is as equimolar as possible is to be generated, which can be directly recycled, and a partial stream enriched in H, which is further separated in the cryodistillation.

The work deals with this separation task. The main subject is the development of a technical process based on it and the experimental demonstration of the temperature cycling process in a facility.

A concept for the separation of the isotopes was developed that combines two separation principles: Gaseous diffusion and hydrogen-metal interactions in a cyclic process. The approach is based on intensive research, meets the requirements of a fusion power plant, incorporates literature analyses, reflects the best possible evaluation of known separation processes and underpins the new two-stage process with theoretical process analyses.

Membranes are used as the first stage. Membranes are usually used for gas separation applications, but not for the separation of the different hydrogen isotopes. The positive separation effect of membranes was included in the process development and proven in experiments. For the DEMO upscale, a tritium reduction of 17 % can be achieved.

As a second stage, hydrogen-metal interactions are exploited, which so far have primarily been used for hydrogen storage and not for separation. For our purpose, the properties of two different materials were analysed to demonstrate the isotope effect and to show the behaviour of temperature and pressure in a specially developed Sieverts test rig. Pd and $TiCr_{1.5}$ proved to be suitable candidates.

In a next step, a test facility was designed and set up to experimentally investigate the two separation stages. The experimental separation of the hydrogen isotopes was successfully demonstrated and validated with an adapted simulation model. A total of three parameter studies were carried out for this stage. The parameter with the best result (separation effect over time) was used for the next study. In the first study, four temperature differences in the possible operating range were compared, with 288-383 K yielding the best result. In the second parameter study, three different process variations were carried out, with one clearly qualifying as the best. In the final study, three different numbers of cycles were compared (3, 5 and 10), with 3 cycles proving to be the best setting. The final procedural variation demonstrated enrichments for $H_2$ from 42.2% to 66.5% and for $D_2$ from 57.8% to 78.5%.

A scale-up in relation to DEMO based on the best parameters determined in the trials showed that the two-stage principle can meet the requirements. The membrane stage is essential to reduce the high tritium inventory. The thermal cycling stage is essential for the removal of protium.

This work will be continued in a follow-up work.

# Dr. Ruslan Popov

**Influence of oxygen annealing on structural and transport properties of pristine $BaHfO_3$ nanocomposite $GdBa_2Cu_3O_{7-\delta}$ films**

In recent years, coated conductors (CC) containing a high – temperature superconducting layer have been shown to be a promising solution for the development of large-scale applications such as motors, generators, fault current limiters, superconducting magnetic storage devices. One of the major requirements for such applications is the ability to carry large currents at various temperatures and magnetic fields.

$GdBa_2Cu_3O_{7-\delta}$ (GdBCO) superconducting thin films prepared by a pulsed laser deposition have a high transition temperature ($T_c$) and relatively critical current densities ($J_c$). GdBCO has a large density of growth-related defects and $J_c$ is dependent on the interaction of "flux lines" penetrating the superconductor in the "mixed phase" with these defects. Therefore, in the recent years the main strategy to push $J_c$ even further was increasing of the density of these defects.

Oxygen annealing, which is an important step during thin films preparation, introduces additional oxygen atoms into GdBCO and forms the superconducting phase. Therefore, the main goals of this work were improvement of $J_c$ by the oxygen annealing, in particular by such parameters as annealing temperature ($T_{ann}$), annealing time ($t_{ann}$) and oxygen pressure ($PO_2$), look for the possibility to tailor the defect morphology by varying the oxygen annealing parameters and improve $J_c$ in GdBCO thin films containing $BaHfO_3$ (BHO) nanocomposites.

Studying the oxygen annealing in pristine and 2.5wt% BHO-nanocomposite GdBCO, several important features were observed:

1. $T_{ann}$: Predominantly affects the stacking faults in the GdBCO matrix. All films showed the highest in-field $J_c$ for 450 °C (the lowest $T_{ann}$ investigated).
2. $PO_2$: Primarily affects the size of Gd-rich nanoparticles present in the GdBCO matrix.
3. $T_{ann}$ for GdBCO+2.5wt% BHO: Compared to pristine GdBCO, BHO nanocomposite GdBCO thin films show the highest in-field $J_c$ at $T_{ann}$=700 °C.

Combining all features observed from studies of influence of Tann, tann and $PO_2$, it was suggested that in pristine GdBCO thin films two approaches can be used to modify the defect morphology:

1. High T, high $PO_2$ processing with consequent cooling to room temperature: This path preserves the stacking faults present in the GdBCO matrix and reduces the density of Gd-rich nanoparticles.
2. High T, low $PO_2$ processing and Low T, high $PO_2$ annealing: This path preserves Gd-rich nanoparticles and reduces the density of stacking faults.

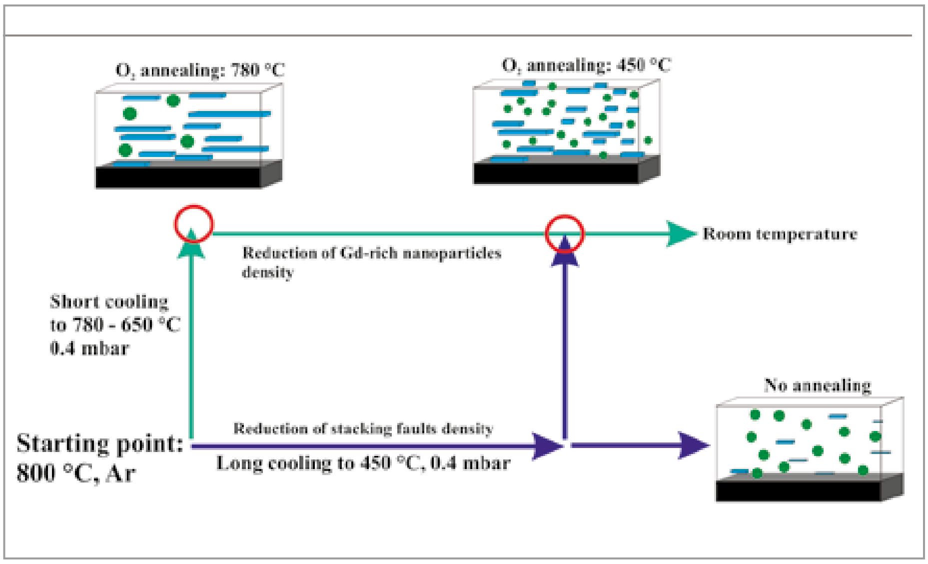



**Fig. 1: Diagram showing two paths for modifying the defect morphology for pristine GdBCO thin films.**

# Dr. Fabian Schreiner

**Development and test of a superconducting generator demonstrator for wind turbines**

The increasing demand for inexpensive, renewable energy sources is causing a continuing trend towards wind power plants of higher performance classes. Generators in these power classes are usually particularly heavy and have in-creased requirements in terms of con-struction space. Superconducting materi-als with their high current carrying capac-ity show the potential for increased pow-er density of electrical machines in terms of weight and volume. At the same time, the demand for rare earths can be dras-tically reduced compared to conventional, permanently excited generators. The work therefore deals with the develop-ment and testing of a generator demon-strator with field excitation coils consist-ing of high-temperature superconductors. For improved electrical and thermal stabil-ity, the superconducting coils are de-signed as non-insulated coils and have no electrical insulation between the coil windings.

Within the scope of the dissertation, a detailed electromagnetic, thermal and mechanical design of a superconducting generator demonstrator is developed. In this context, not only the interaction of the mentioned physical domains among each other, but also the basic practical feasibility is considered. The superconducting field excitation coils are located in the stator of the machine, while the normally conducting three-phase winding is of rotating design. Furthermore, the stator and rotor are implemented as so-called air gap wind-ings. This means that the windings are not inserted in slots as in conventional rotating field machines. Cryogenic cooling is achieved by direct conduction cooling with two cryocoolers. The coolers are of two-tube design with the respective operating temperatures at 77 K and 30 K. The rated power of the demonstrator is 10 kW at a speed of 389 min-1 and a torque of 250 N m. The average magnet-ic flux density in the air gap is 0.63 T at a nominal excitation current of the super-conducting field coils of 450 A. The heat inputs from the current leads, from the mechanical support structures and from thermal radiation are 44.64 W, 15.87 W and 4.12 W for the first cooling stage and 0.89 W, 2.89 W and 0 W for the second cooling stage, respectively.

The design of the superconducting generator demonstrator is shown in Figure 1.

For the construction of the demonstrator, 14 so-called pancake coils were devel-oped and manufactured, which in a later step were joined together to form seven double pancake coils. High-temperature superconductors from two different man-ufacturers were used. All coils were pre-characterized in liquid nitrogen at 77 K and met the minimum critical current requirement. However, the coils with critical currents ranging from 122.4 A to 283.6 A showed a large scatter. The delays in charging time, due to the lack of winding insulation, ranged from 13.1 s to 43.2 s for the different double pan-cake coils. In total, only six double pan-cake coils were needed for the stator system. The seventh coil was subjected to further testing under conduction cooled conditions at temperatures below 77 K. Non-insulated superconducting coils exhibit additional losses during transient charging and discharging. In order to better estimate the behavior of the coils, a transient thermal-electrical model was developed that shows good agreement with the measured maximum coil temper-atures during transient processes. Fur-thermore, the improved electrical and thermal stability of the non-insulated coil could be verified. Despite a continuous load of 1.5 times the critical current, the coil showed no damage.

Cooling of the entire system took just under 48 hours. During this time, all coils reached temperatures below 20 K. At the adjusted operating temperature of 30 K, the coil system reached a critical current of 695.4 A and thus met the require-ments for operating current. The alter-nating magnetic poles required for gen-erator operation were also confirmed by measurement. Figure 2 shows the super-conducting generator demonstrator on an engine test bench at the East Campus.

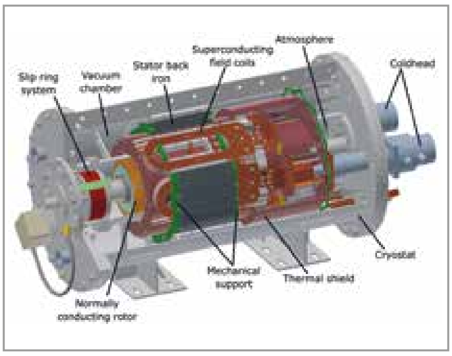



**Fig. 1: Design of the superconducting generator demonstrator.**

**Fig. 2: Superconducting generator demonstrator on the engine test bench at Campus East.**

# Lectures, Seminars, Workshops

### KIT-Fakultät Elektrotechnik und Informationstechnik

- **Praktikum Supraleitende Materialien** (Holzapfel, Hänisch) SS 22, WS 22/23
- **Energy Storage and Network Integration** (Grilli, De Carne) WS 21/22, WS 22/23

  **Tutorial for Energy Storage and Network Integration** (Noe, Grilli, De Carne, Kottonau, Karrari) WS 21/22, WS 22/23

  **Superconductivity for Engineers** (Holzapfel, Kempf) WS 21/22, SS 22, WS 22/23

  **Exercise for superconductivity for Engineers** (Hänisch) WS 22/23

  **Seminar on Applied Superconductivity** (Arndt, Holzapfel, Kempf) SS 22, WS 22/23

  **Superconducting Materials Part I** (Holzapfel) WS 21/22, WS 22/23

  **Superconducting Materials Part II** (Holzapfel) SS 22

  **Superconducting Magnet Technology** (Arndt) SS 22

  **Seminar Strategieableitung für Ingenieure** (Arndt) WS 21/22, SS 22, WS 22/23

  **Superconducting Power Systems** (Arndt, Pham, Müller, Grilli, Schreiner, De Sousa) WS 21/22, SS 22, WS 22/23

  **Praktikum Robotische Wickeltechnik für Supraleiterdrähte** (Arndt) WS21/22, SS 22, WS 22/23

  **Superconductors for Energy Applications** (Grilli) WS 21/22, SS 22, WS 22/23

  **Übungen zu Superconductors for Energy Applications** (Grilli) SS 22, WS 22/23

  **Electrical and Electronic Engineering for Mechanical Engineers** (De Carne) WS 21/22, WS 22/23

  **Tutorial for Electrical Engineering and Electronics for Mechanical Engineers** (De Carne) WS 22/23

### KIT-Fakultät für Chemieingenieurwesen und Verfahrenstechnik

- **Vakuumtechnik** (Day, Varoutis) WS 21/22, WS 22/23
- **Übung zu Vakuumtechnik** (Day, Varoutis) WS 21/22, WS 22/23

### KIT -Fakultät Maschinenbau

- **Fusionstechnologie A** (Day, Größle, Fietz, Weiss, Wolf) WS 21/22, WS 22/23

### House of Competence

- **„Netzwerken – Verbindungen schaffen Freiheiten“ (Arndt), SS 22, WS 22/23, Tagesworkshop**

## Seminare

### Kryo-Seminare

- **09.-11.03.2022** (Neumann)
- **28.-30.09.2022** (Neumann)

### Duale Hochschule BW – Fachbereich Maschinenbau

- **Arbeitssicherheit und Umweltschutz** (Bauer) WS 21/22, SS 22, WS 22/23
- **Tieftemperaturtechnik** (Neumann) WS 21/22
- **Thermodynamik Grundlagen 2** (Neumann) WS 21/22
- **Thermodynamik Grundlagen 1** (Neumann) SS 22

# Completed PhD Theses

(* Academic supervisor)

## ENERGY

**Alexander Buchholz**
Prospective Life Cycle Assessment of High-Temperature Superconductors for Future Grid ApplicationsBetreuer: Dr. M. Weil (ITAS), Prof. Dr.-Ing. M. Noe *

**Dustin Kottonau**
Echtzeitsimulation und Netzintegration einer Mikrogasturbine
Betreuer: Prof. Dr.-Ing. M. Noe*

**Fabian Schreiner**
Development and test of a technology wind generator demonstrator with no insulation field coils applying high temperature superconductors
Betreuer: Prof. Dr.-Ing. M. Doppelbauer (KIT, ETI), Prof. Dr.-Ing. M. Noe*

## MATERIAL

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

**Ruslan Popov**
Influence of oxygen annealing on structural and transport properties of pristine and $BaHfO_3$ nanocomposite $GdBa_2Cu_3O_{7-\delta}$ films
Betreuer: Dr. J. Hänisch,
Prof. Dr. B. Holzapfel (KIT, ETIT)*

## VAKUUM

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

**Yannick Hörstensmeyer**
Holistische Modellierung des Brennstoffkreislaufs eines zukünftigen FusionsreaktorsBetreuer: Dr. C. Day,
Prof. Dr.-Ing. R. Stieglitz (INR)*

**Cyra Neugebauer**
Untersuchung zur semi-kontinuierlichen Separation von Wasserstoff-Isotopen für die FusionBetreuer: Dr. C. Day,
Prof. Dr. R. Stieglitz (KIT, Mach)*

# Completed Master Theses
(* Academic supervisor)

## ENERGY

**Stefanelli Lorenzo**
Rowen's Model application for non-real-time and real-time simulation of Micro Gas TurbinesBetreuer: D. Kottonau, Prof. Eng. M. Marconcini (University of Florence)*

**Mauro Semeraro**
Modelling complexity reduction of AC distribution grids
Betreuer: Dr. G. de Carne,
Prof. Dr.-Ing. M. Noe*

**Judy Bavaro**
H∞ Robust Control of a HESS for frequency regulation
Betreuer: Dr. G. de Carne,
Prof. Dr.-Ing. M. Noe*

**Irene Goiria**
Optimization of Hybrid Energy Storage Systems Under Different Control Approaches-Betreuer: M. Maroufi, Dr. G. de Carne*

**Ander Retamosa Garcia**
Micro Gas Turbine thermal emulator set-up in a real-time environment
Betreuer: D. Kottonau, Dr. G. de Carne*

**Xiaochang Liu**
Stability Analysis of Power Hardware in the Loop with Impedance-based modeling approach using Grid converters
Betreuer: Dr. G. de Carne,
Prof. Dr.-Ing. M. Noe*

**Ziyang Li**
Untersuchung einer schnell taktenden LLC Wandlerstufe im Sub-MHz / MHz Bereich in verschiedenen Ausgangleistungsklassen
Betreuer: Dr. G. de Carne,
Prof. Dr.-Ing. M. Noe*

**Han Zhang**
Modeling and Analysis of a PEM Electrolysis System for Parallel Simulation
Betreuer: N. Nemsow, Dr. G. de Carne *

## VAKUUM

**Alexander Zilz**
Investigation of the Rarefied Gas Flow in the Pumping Tube of a $^3He/^4He$ Dilution Refrigerator
Betreuer: Dr. Tantos,
Prof. Dr.-Ing. S. Grohmann (ITTK)*

## MATERIAL

**Johannes Weis**
Thermal Resistance Measurement over Solid-Solid Interfaces
Betreuer: Dr. N. Bagrets, Dr. K. Weiss*

# Completed Bachelor Theses

(* Academic supervisor)

## ENERGY

**Julian Bell**
Entwicklung eines didaktischen Konzepts für die Station „Windenergie“ im KIT-Schülerlabor Energie
Betreuer: A. Rimikis, Prof. Dr. B. Holzapfel*

**Nicolas Dworschak**
Entwicklung eines didaktischen Konzeptes für die Station „Wasserstoffmobilität“ im KIT-Schülerlabor Energie
Betreuer: A. Rimikis, Prof. Dr. B. Holzapfel*

**Florian Steinhauser**
Entwicklung einer Messroutine für kritische Ströme von Supraleitern
Betreuer: Dr. J. Hänisch,
Prof. Dr. B. Holzapfel*

## KRYO

**Simon Urban**
Konstruktion einer Füllstandsonde für flüssigen Wasserstoff
Betreuer: S. Bobien, M. Kastner (DH)*

## MAGNET

**Maximilian Korb**
Elektromagnetische Auslegung eines HTS-Gyrotron-Magneten
Betreuer: Dr. F. Hornung,
Prof. Dr. T. Arndt*

# Lectures and Guest Presentations

**16. März 2022**
Characterization of HTS material for electrical engineering applications
Prof. Bruno Douine University of Lorraine
Gastvortrag, IB Supra

**31. März 2022**
Impact of local strain on the screening currents induced in 2G HTS insert magnets of high DC magnetic field generation
Prof. Frederic Trillaud UNAM – National Autonomous University of Mexico
Gastvortrag, IB Supra

**08. September 2022**
Low Inertia Systems: Complex Frequency and Simple Control.
Prof. Federico Milano
Gastvortrag, IB Energie

**28. September 2022**
Interpretation of divertor detachment in JET using edge fluid codes
Prof. Mathias Groth
Aalto University, Espoo, Finland
Gastvortrag IB Vakuum

**15. November 2022**
Understanding the real, imperfect nature of REBCO (REBa2Cu3Ox with RE=Rare Earth elements) coated conductors and implications for ultra-high magnetic field used
Prof. David Larbalestier
Chief Materials Scientist of the National High Magnetic Field Laboratory & Professor of Mechanical Engineering Applied Superconductivity Center and Florida State University, Tallahassee, Florida, USA
Fachvortrag ITEP/IQMT, IB Supra

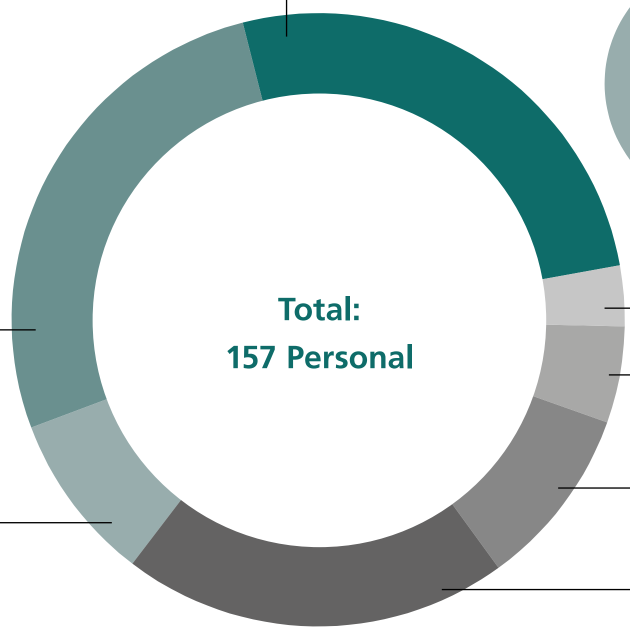
**08. Dezember 2022**
Grid forming power converters. Principles and applications
Prof. Pedro Rodriguez
Gastvortrag, IB Energie

# Research Fields and Topics

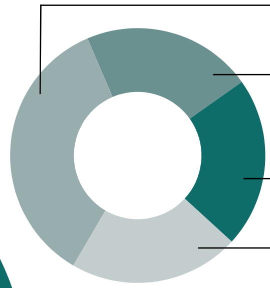
| Superconducting and Cryomaterials (Holzapfel) | Energy Applications (Noe) | Superconducting Magnet Technology (Arndt) | Fusion Fuel Cycle Technologies (Day) |
|---|---|---|---|
| Superconducting Materials (Hänisch) | Superconducting Power System Components (Noe) | Coil and Magnet Technology (Hornung) | 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, 2022)**




**Additional staff in 2022:**



# Guest Researcher

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

**J. Shi**
23.10.21–15.09.22
Southwest Jiaotong University, Sichuan, P.R. China

**J. Zhang**
26.10.21–17.10.22
Southwest Jiaotong University, Sichuan, P.R. China

**M. Tian**
17.01.22–14.04.22
University of Cambridge, Cambridge, UK

**J. Wang**
22.01.22–20.07.22
North China Electric Power University, Bei Jing, P.R. China

**Prof. Dr. B. Douine**
04.04.22–31.05.22
University of Lorraine; Green Lab, Lorraine, Frankreich

**D. Fusco**
01.09.22–31.12.22
University of Cassino and Southern Lazio, Lazio, Italy

**C. Chow**
03.11.22–02.04.23
University of Hongkong, Hongkong

# Memberships

## of relevant technical and scientific organisations

### Tabea Arndt

- Programmkomitee der Tagung ZIEHL, 04.-05.04.2022, Berlin
- International Organizing Committee Conference Magnet Technology, MT
- International Organizing Committee Conference EUCAS, Large Scale
- International Organizing Committee Conference CCA, Large Scale
- Mitglied DKE TC90
- Delegierte zum Technology Cooperation Program High-Temperature Superconductivity der International Energy Agency
- Mitglied des Magnet Panel der Muon-Collider-Aktivität, CERN
- Mitglied des Kuratoriums der EnBW-Stiftung
- „Forschungsfeld Hochtemperatur-Supraleitung" des BMWi, Kuratorin seit Ende 2021

### Nadja Bagrets

- Expertin innerhalb des Arbeitsfeldes TWA16 der VAMAS (Versailles Project on Advanced Materials and Standards bei ISO) zur Durchführung von Ringversuchen
- Expertin im Komitee K 184 „Supraleiter" der deutschen Kommission Elektrotechnik (DKE) im DIN
- Expertin im technischen Komitee TC90 „Supraleiter", Arbeitsgruppe WG5 der internationalen elektrotechnischen Kommission (IEC)

### Kai Bauer

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

### Christian Day

- Mitglied des Vorstandsrates der Dt. Vakuumgesellschaft (DVG).
- Projektleitung des Bereichs Tritium-Materiezufuhr-Vakuum (TFV) im Europäischen Fusionsprogramm EUROFUSION
- Sprecher Topic ‚Vakuum und Tritium' der deutschen DEMO-Initiative
- Mitglied im International Advisory Committee der RGD (Rarefied Gas Dynamics Conference)
- Mitglied des Programmkomitees der ISFNT (international Symposium of Fusion Nuclear Technology).
- Chartered Engineer der American Vacuum Society (AVS).
- Mitglied im Team zur Erarbeitung des Forschungsplans von DTT, verantwortlich für Fusionstechnologie.
- Mitglied im Board der IAEA Technical Meeting Reihe Brennstoffkreislauf

### Giovanni de Carne

- Leiter des IEEE Power and Energy Society "Task Force on Solid State Transformer integration in distribution grids"
- Helmholtz Nachwuchsgruppen-Leiter – 2020
- Chairman der IEEE PES Task Force "Solid State Transformer integration in distribution grids"
- Sekretär und Mitglied der CIGRE Arbeitsgruppe B4.91 "Power electronics-based transformer technology, design, grid integration and services provision to the distribution grid"
- Mitglied der CIGRE Arbeitsgruppe A3.40 "Technical requirements and field experiences with MV DC switching equipment"
- Mitglied der IEEE Arbeitsgruppe P2004"Hardware in the Loop".
- Mitglied der IEEE Arbeitsgruppe "Modelling and Simulation with High Penetration of Inverter-Based Renewables"
- Assozieirter Editor der IEEE Zeitschrift „IEEE Open Journal for Power Electronics"
- Assoziierter Editor der IEEE Zeitschrift "IEEE Industrial Electronic Magazine"
- Assoziierter Editor der Springer Zeitschrift "Electrical Engineering – Archiv für Elektrotechnik"
- Mitglied beim „Institute of Electrical and Electronics Engineers"
- Mitglied beim Verband der Elektrotechnik, Elektronik und Informationstechnik

**Francesco Grilli**

- Vorstandsmitglied der Europäischen Gesellschaft für angewandte Supraleitung (ESAS)

**Jens Hänisch**

- Superconductor Science and Technology, Mitglied im Editorial-Board
- European Magnetic Field Laboratory EMFL, Mitglied im User Proposal Selection Committee
- Mitglied im KIT-Konvent

**Bernhard Holzapfel**

- European Conference on Applied Superconductivity, Member of International Program Committee
- International Symposium on Superconductivity (ISS), Member of International Program Committee
- Member of the Scientific Advisory Board of ICMAB-CSIC
- Coated Conductor for Applications (CCA), Member of International Program Committee

**Holger Neumann**

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

**Mathias Noe**

- Kurator des Forschungsnetzwerkes Hochtemperatur-Supraleitung des BMWi
- Internationaler Experte der CIGRE D1.69 Arbeitsgruppe"Assessing emerging test guidelines for HTS applications in power systems"
- Internationaler Experte der CIGRE Arbeitsgruppe D1.64 "Cryogenic dielectric insulation"
- Deutscher Abgesandter der International Energy Agency, Technology Cooperation Programm Hochtemperatur-Supraleitung
- Mitglied des Boards der Applied Superconductivity Conference
- Mitglied des Interessenverbandes Supraleitung (ivsupra)
- Mitglied der Arbeitsgruppe zur Erstellung einer Beschleuniger F&E Roadmap im Rahmen einer europäischen Strategie für Teilchenphysik

**Sonja Schlachter**

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

**Wescley T. B. de Sousa**

- Vorstandsmitglied des „HTS Modelling Workgroup"
- Vorstandsmitglied des COST ACTION CA19108 – „High-Temperature SuperConductivity for AcceLerating the Energy"
- Experte in der CIGRE Arbeitsgruppe B4/A3.86 - Strombegrenzungstechnologien für DC-Netze
- Technischer Editor der IEEE Zeitschrift IEEE „Transactions on Applied Superconductivity"

**Stylianos Varoutis**

- Mitglied im wissenschaftlichen Komittee der NEGF (European Conference on Non-equilibrium Gas Flows).
- Mitglied im Auswahlkomittee des EU High Performance Computers MARCONI
- Mitglied im Europa/Japan-Auswahlkommittee für Großrechnersimulationen im „Broader Approach"
- Mitglied der Deutschen Vakuumgesellschaft (DVG)
- Vorsitzender des Fachverbandes Vakuumphysik und –technik der Dt. Physikalischen Gesellschaft (DPG).

**Klaus-Peter Weiss**

- DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE Referat K 184 „Supraleiter", Obmann
- IEC International Electrotechnical Commission/Technical Comittee 90 „Superconductivity", Mitglied
- DIN NA 062-01-42 AA „Zug- und Duktilitätsprüfung für Metalle" Mitglied
- ISO ISO/TC 164/SC 1 "Uniaxial Testing" Mitglied
- Sprecher der Arbeitsgruppe „Magnet Design" innerhalb der deutschen Koordination der Fusionsforschung für DEMO
- Member of the International Technical Program Committee – Workshop on Mechanical and Electromagnetic Properties of Composite Superconductors / Organisator MEM2022 10th Workshop in Karlsuhe
- Board Member ICMC (International Cryogenic Materials Conference) & Subcommittee International Cryogenic Material Library
- Experte im EUROfusion Scientific & Technical Advisory Committee (STAC)

# Fusion

## Journal article

U. Stroth et al. [incl. Chr. Day and S. Varoutis]
Progress from ASDEX Upgrade experiments in preparing the physics basis of ITER operation and DEMO scenario development, Nuclear Fusion 62 (2022) 042006.
doi: 10.1088/1741-4326/ac207f // Open access

Chr. Day, K. Battes, B. Butler, et al.
The Pre-Concept Design of the DEMO Tritium, Matter Injection and Vacuum Systems, Fusion Engineering and Design 179 (2022) 113139.
Doi: 10.1016/j.fusengdes.2022.113139 // Open access

T. Haertl, Chr. Day, T. Giegerich, et al.
Design and feasibility of a pumping concept based on tritium direct recycling Fusion Engineering and Design 174 (2022) 112969.
Doi: 10.1016/j.fusengdes.2021.112969 // Open access

D. S. Nickel, N. Bagrets, W. H. Fietz, et al.
Subscale HTS Fusion Conductor Fabrication and Testing in High Magnetic Background Field
IEEE Transactions on Applied Superconductivity, vol. 32, no. 4, pp. 1-7, June 2022, Art no. 4200907, doi: 10.1109/TASC.2022.3151581

M.Q. Tran, P. Agostinetti, G. Aiello, et al.
Status and future development of Heating and Current Drive for the EU DEMO, Fusion Engineering and Design 180 (2022) 113159.
Doi: 10.1016/j.fusengdes.2022.113159 // Open access

J. C. Schwenzer, C. Day, T. Giegerich, et al.
Operational Tritium Inventories in the EU-DEMO Fuel Cycle, Fusion Science Technology 78 (2022) 664-675.
Doi: 10.1080/15361055.2022.2101834 // Open access

T. Teichmann, T. Giegerich, Chr. Day
Simulation of Mercury Driven Diffusion Pumps for Torus Exhaust Pumping, IEEE Trans. Plasma Science 50 (2022) 4459-4464.
Doi: 10.1109/TPS.2022.3202083

P.T. Lang, T. Bosman, Chr. Day, et al.
ASDEX Upgrade Team, Concept for a multi-purpose
EU-DEMO pellet launching system, Fusion Engineering and Design 185 (2022) 113333.
Doi: 10.1016/j.fusengdes.2022.113333 // Open access

B. Ploeckl, P.T. Lang, Chr. Day, et al.
Testbed for the Pellet Launching System for JT-60SA, Fusion Engineering and Design 186 (2023) 113370.
Doi: 10.1016/j.fusengdes.2022.113370 // Open Access

C. Tantos, S. Varoutis, C. Day, et al.
DSMC simulations of neutral gas flow in the DTT particle exhaust system, Nuclear Fusion 62 (2022) 026038.
doi:10.1088/1741-4326/ac42f5

M. Yoshida et al. [incl. Chr. Day]
Plasma physics and control studies planned in JT-60SA for ITER and DEMO operations and risk mitigation, Plasma Phys. Control. Fusion 64 (2022) 054004.
Doi: 10.1088/1361-6587/ac57a0 // open access

Y. Kamada et al. [incl. C. Day and H. Strobel]
Completion of JT-60SA construction and contribution to ITER, Nuclear Fusion 62 (2022) 042002.
doi: 10.1088/1741-4326/ac10e7

T. Sunn Pedersen et al. [incl. C. Day, S. Varoutis, C. Tantos]
Experimental confirmation of efficient island divertor operation and successful neoclassical transport optimization in Wendelstein 7-X, Nucl. Fusion 62 (2022) 042022.
Doi: 10.1088/1741-4326/ac2cf5 // open access

C. Tantos, E. Kritikos, S. Varoutis, et al.
Kinetic modeling of polyatomic heat and mass transfer in rectangular microchannels, Heat and Mass Transfer (2022).
Doi: 10.1007/s00231-022-03224-z // open access

## Proceedings

D. Sánchez-Herranz, O. Nomen, B. Kumar, et al.
Status of the Engineering Design of the IFMIF-DONES high energy beam transport line and beam dump system, Proc. 13th International Particle Accelerator Conference (IPAC'22), Bangkok, Thailand, 12–17 June 2022, pp. 2520-2523.
doi:10.18429/JACoW-IPAC2022-THPOST035

I. Podadera, A. Ibarra, M. Weber, et al.
Commissioning Plan of the IFMIF-DONES Accelerator, LINAC-22 31st International Linear Accelerator Conference, Liverpool, UK, 28 Aug-2 Sep 2022, pp. 330-333.
doi:10.18429/JACoW-LINAC2022-TUPOJO01

P. T. Lang, M. van Berkel, W. Biel, et al.
ASDEX Upgrade Team, Real time monitoring of pellet delivery to facilitate burn control in EU-DEMO, 48th EPS Plasma Conference, virtual, 27–30 June 2022.
https://indico.fusenet.eu/event/28/contributions/277/attachments/291/700/Paper_Final.pdf

## Book essay

Y.N. Hörstensmeyer
Holistic fuel cycle modelling of a future fusion reactor = Holistische Modellierung des Brennstoffkreislaufs eines zukünftigen Fusionsreaktors; KITopen, July 2022.
DOI: 10.5445/IR/1000148749

C. Gleason González
Modelling and validation of neutral particle flow by means of stochastic algorithms using the example of a fusion divertor
KITopen, November 2022.
DOI: 10.5445/IR/1000152187

## Presentation

X. Luo, S. Hanke, K. Battes, et al.
Monte Carlo Simulation Studies to Support an Integrated Design for the Cryogenic Vacuum Systems of the Einstein Telescope, 68th Int. Symp. of the American Vacuum Society, Pittsburg, PA, USA, 6–11 Nov 2022.

S. Merli, A. Schulz, M. Walker, et al.
Self-Consistent Modelling of a Linear Microwave Plasma Source in a Magnetic Field, DPG Meeting 2022, Mainz, 28–21 Mar 2022.

Chr. Day, K. Battes, S. Hanke, et al.
Vacuum system simulations for the Einstein Telescope LF section, 1st Gravitational Wave Detector Vacuum Workshop, La Biodola, Italy, 28–30 Sept 2022.

S. Hanke, K. Battes, Chr. Day, et al.
Technical concepts and potential solutions for the vacuum challenges of the LF tower, 1st Gravitational Wave Detector Vacuum Workshop, La Biodola, Italy, 28–30 Sept 2022.

P. T. Lang, L.R. Baylor, Ch. Day, et al.
Plasma fuelling on ITER and new requirements for DEMO, IAEA Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy, Vienna, Austria, 11–13 Oct 2022.

D. Naujoks, A. Kharwandikar, V. Haak, et al.
Divertor concept development for the W7-X stellarator experiment, 4th IAEA Technical Meeting on divertor concepts, Vienna, Austria, 7–10 Nov 2022.

T. Kremeyer, D. Boeyaert, Chr. Day, et al.
Complete H fuel cycle with the island divertor in Wendelstein 7-X, 4th IAEA Technical Meeting on divertor concepts, Vienna, Austria, 7–10 Nov 2022.

F. Siviero, M. Mura, B. Busetto, et al.
Getter pump mock-up in view of application in modern Neutral Beam Injectors, XXV Conference of the Italian Vacuum Society, Naples, Italy, 10–12 May 2022.

Y. Kathage, Chr. Day
Validation of hydrogen plasma simulation using optical emission spectroscopy, 94th IUVSTA Workshop on reliable sensing and control of reactive plasmas, Kranjska Gora, Slovenia, 29 May – 2 June 2022.

S. Hanke, X. Luo, K. Battes, et al.
Simulations of vacuum conditions in the beam pipe and around the cryogenic mirror of the Einstein Telescope, 22nd Int. Vacuum Congress IVC-22, Sapporo, Japan, 11–16 Sep 2022.

K. Battes, S. Hanke, Chr. Day
Alternative structural materials and their outgassing behaviour, 22nd Int. Vacuum Congress IVC-22, Sapporo, Japan, 11–16 Sep 2022.

S. Hanke, T. Giegerich, Chr. Day, et al.
Pumping performance of metal foils, 22nd Int. Vacuum Congress IVC-22, Sapporo, Japan, 11–16 Sep 2022.

X. Luo, Chr. Day
Topological impact of a simple self-replication geometric structure with great application potential in vacuum pumping and photovoltaic industry, 32nd Int. Symp. on Rarefied Gas Dynamics, Seoul, Korea, 4–8 July 2022.

T. Teichmann, T. Giegerich, Chr. Day
A Direct Simulation Monte Carlo Framework for the Simulation of Mercury Driven Diffusion Pumps for Fusion Reactor Exhaust Pumping, 32nd Int. Symp. on Rarefied Gas Dynamics, Seoul, Korea, 4–8 July 2022.

C. Tantos, A. Zilz, Chr. Day, et al.
Numerical cooling power predictions for a dilution refrigerator via kinetic modeling, 32nd Int. Symp. on Rarefied Gas Dynamics, Seoul, Korea, 4–8 July 2022.

S. Kunze, P. Perrier, R. Groll, et al.
Predicting rarefied gas flow through surface functionalized channels, 32nd Int. Symp. on Rarefied Gas Dynamics, Seoul, Korea, 4–8 July 2022.

A. Santucci, G. Cortese, V. Narcisi, et al.
Impact of DEMO nuclear buildings air ventilation on the Exhaust Detritiation System, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

M. Dalla Palma, G. Barone, A. Cucchiaro, et al.
Design of DTT vacuum vessel, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

S. Roccella, P. Innocente, G. Dose, et al.
Design and qualification activities of the First Divertor in the DTT facility, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

P. T. Lang, M. van Berkel, W. Biel, et al.
Real time monitoring of pellet delivery to facilitate burn control in EU-DEMO, 48th EPS Plasma Conference, virtual, 27–30 June 2022.

C. Tantos, S. Varoutis, Chr. Day
Transient deterministic modeling of neutral gas flow in DEMO particle exhaust system, 3rd Fusion HPC Workshop, virtual, 15–16 Dec 2022.

S. Varoutis, C. Tantos, C. Day, et al.
Deterministic and stochastic modelling of particle exhaust in the sub-divertor region of W7-X, 3rd Fusion HPC Workshop, virtual, 15–16 Dec 2022.

T. Giegerich, C. Day, A. Santucci, et al.
Design considerations and latest architecture of the EU-DEMO fuel cycle inner loops, 13th Int. Conf. On Tritium Science and Technology, Bucharest, Romania, 16–21 Oct 2022.

## Posters

Yu. Igitkhanov, T. Giegerich, Chr. Day
Fuel purification requirements in a Fusion Power Plant, IAEA Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy, Vienna, Austria, 11–13 Oct 2022

T. Giegerich, J. Igitkhanov, J.C. Schwenzer, et al.
Actuators for plasma operation by the DEMO fuel cycle inner loops, IAEA Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy, Vienna, Austria, 11–13 Oct 2022.

C. Tantos, S. Varoutis, Chr. Day
Self-consistent modeling of the interface between the divertor and the pumping system in DTT, IAEA Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy, Vienna, Austria, 11–13 Oct 2022.

G. Dose, S. Rocella, P. Innocente, et al.
An overview of the conceptual design of the plasma-facing components of the DTT divertor, 4th IAEA Technical Meeting on divertor concepts, Vienna, Austria, 7–10 Nov 2022.

D. Sánchez-Herranz, O. Nomen, B. Kumar, et al.
Status of the Engineering Design of the IFMIF-DONES high energy beam transport line and beam dump system, 13th International Particle Accelerator Conference (IPAC'22), Bangkok, Thailand, 12–17 June 2022.

I. Podadera, F. Arranz, S. Becerril, et al.
Commissioning Plan of the IFMIF-DONES Accelerator, LINAC-22 31st International Linear Accelerator Conference, Liverpool, UK, 28 Aug–2 Sep 2022.

I. Ivanova-Stanik, P. Chmielewski, Ch. Day, et al.
Divertor power spreading in Divertor Tokamak Test facility for full power scenario with Ar and Ne seeding, 25th Int. Conf. on plasma surface interaction, virtual, 12–17 June 2022.

Yu. Igitkhanov, Chr. Day, S. Varoutis, et al.
Vortices formation in DEMO divertor during the particle exhaust, 25th Int. Conf. on plasma surface interaction, virtual, 12–17 June 2022.

Y. Kathage, X. Luo, Chr. Day
Implementation of Test Particle Monte-Carlo codes in the Development of a Metal Foil Pump, 32nd Int. Symp. on Rarefied Gas Dynamics, Seoul, Korea, 4–8 July 2022.

Chr. Day, J. Ayllon-Gerola, S. Davis, et al.
Design of the JT-60SA divertor cryopumps, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

S. Hanke, Ch. Day, T. Giegerich, et al.
Experimental characterisation of a large NEG pump towards its application in DEMO neutral beam injectors, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

G. Cortese, A. Santucci, J. C. Schwenzer, et al.
Review of Wet Scrubber Columns technology and preliminary dimensioning for Exhaust Detritiation System in DEMO, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

Y. Kathage, A. Vazquez Cortes, T. Giegerich, et al.
Hydrogen plasma simulation results and their experimental validation via optical emission spectroscopy, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

J.C. Schwenzer, Chr. Day
EU-DEMO fuel cycle performance metrics and tritium selfsufficiency criteria, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

T. Teichmann, T. Giegerich, Chr. Day
Direct Simulation Monte Carlo of Mercury Driven Linear Diffusion Pumps for EUDEMO Torus Exhaust Pumping, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

A. Uihlein, T. Giegerich, Chr. Day
Hydrogen Isotope Separation process development for the EU-DEMO Fuel Cycle, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

A. Vazquez Cortes, Y. Kathage, S. Hanke, et al.
HERMESplus Experimental Campaigns with Nb and V as Membrane Materials, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

P.T. Lang, T. Bosman, Chr. Day, et al.
ASDEX Upgrade Team, Concept for a multi-purpose EU-DEMO pellet launching system, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

B. Ploeckl, P.T. Lang, Chr. Day, et al.
Testbed for the Pellet Launching System for JT-60SA, 32nd SOFT, Dubrovnik, Croatia, 18.–23. Sept 2022.

J.C. Schwenzer, A. Santucci, Chr. Day
Modeling of the HCPB He-CPS for EU-DEMO – Process simulations of molecular sieves & NEG sorbents, TOFE-22, Anaheim, CA, USA, 12–16 June 2022.

A. Uihlein, T. Giegerich, Chr. Day
Investigations of a Membrane-Coupled Temperature Swing Absorption Process for Hydrogen Isotope Separation in the EU-DEMO Fuel Cycle, 13th Int.
Conf. On Tritium Science and Technology, Bucharest, Romania, 16–21 Oct 2022.

Y. Kathage, A. Vazquez Cortes, S. Hanke, et al.
Plasma-driven permeation with noble gas admixtures, 13th Int. Conf. On Tritium Science and Technology, Bucharest, Romania, 16–21 Oct 2022.

J.C. Schwenzer, Chr. Day, T. Giegerich, et al.
Water Balance and Water Detritiation Requirements in the EU DEMO, 13th Int.
Conf. On Tritium Science and Technology, Bucharest, Romania, 16–21 Oct 2022.

T. Teichmann, X. Luo, T. Giegerich, et al.
Estimation of the effective pumping speed for deuterium and tritium of the Linear Diffusion Pumps in the EU-DEMO torus exhaust vacuum pumping system, 13th Int.
Conf. On Tritium Science and Technology, Bucharest, Romania, 16–21 Oct 2022.

## Outreach

Thinking big in Vacuum R&D, CERN Courier Vacuum Edition 2022, pp. 5–8
https://cerncourier.com/a/thinking-big-invacuum-rd/

Daniel Clery, OUT OF GAS – A shortage of tritium fuel may leave fusion energy with an empty tank,
Science, Vol 376, Issue 6600.
https://www.science.org/content/article/fusion-power-may-run-fuel-even-gets-started

# Materials and Technologies for the Energy Transition (MTET)

## Journal article

G. dos Santos; F. G. R. Martins; F. Sass; et al.
"A 3-D Finite-Element Method Approach for Analyzing Different Short Circuit Types in a Saturated Iron Core Fault Current Limiter".
IEEE Transactions on Applied Superconductivity vol. 32, no. 3 (2022), p. 5600713.
doi: 10.1109/TASC. 2022.3142047.

F. Huber; W. Song; M. Zhang, et al.
"The T-A formulation: an efficient approach to model the macroscopic electromagnetic behaviour of HTS coated conductor applications".
Superconductor Science and Technology vol. 35, no. 4 (2022), p. 043003.
doi: 10.1088/1361-6668/ac5163.

B. M. Oliveira Santos; G. dos Santos; F. Sirois; et al.
"2-D Modeling of HTS Coils With T-A Formulation: How to Handle Different Coupling Scenarios".
IEEE Transactions on Applied Superconductivity vol. 32, no. 5 (2022), p. 5900804.
doi: 10.1109/TASC. 2022.3160512.

F. Trillaud; E. Berrospe-Juarez; V. M. R. Zermeño, et al..
"Electromagneto-mechanical model of high temperature superconductor insert magnets in ultra high magnetic fields".
Superconductor Science and Technology vol. 35 (2022), p. 054002.
doi: 10.1088/1361-6668/ac4b9f.

C. R. Vargas-Llanos; F. Huber; N. Riva; et al.
"3D homogenization of the T-A formulation for the analysis of coils with complex geometries".
Superconductor Science and Technology vol. 35, no. 12 (2022), p. 124001.
doi: 10.1088/1361-6668/ac9932.

Z. Wen; H. Zhang; M. Tian; et al.
"A statistical model for the design of rotary HTS flux pumps based on deep-learning neuron network".
Superconductivity vol. 3 (2022), p. 100017.
doi: 10.1016/ j.supcon.2022.100017.

A. Lani, V. Sharma, V. F. Giangaspero et al.
A Magnetohydrodynamic enhanced entry system for space transportation: MEESST
Journal of Space Safety Engineering (2022) in press, available online
doi: 10.1016/j.jsse.2022.11.004.

Corato V., Bruzzone P., Bykovskiy N. et al.
Strategy for Developing the EU-DEMO Magnet System in the Concept Design Phase
IEEE Transactions on Applied Superconductivity, vol. 32, no. 6, pp. 1-7, Sept. 2022, Art no. 4201407,
doi: 10.1109/TASC.2022.3153248.

P. Cayado, L. Grünewald, M. Erbe, et al.
Critical current density improvement in CSD-grown high-entropy REBa2Cu3O7−d films, RSC Adv. 12, 28831 (2022)

J. Hänisch, K. Iida, P. Cayado, et al.
Microstructure, pinning properties, and aging of CSD-grown SmBa2Cu3O7−δ films with and without BaHfO3 nanoparticles, Supercond. Sci. Technol. 35 (2022) 084009,
https://doi.org/10.1088/1361-6668/ac7b4d

D. Li, P. Shen, J. Tian, et al.
A disorder-sensitive emergent vortex phase identified in high-Tc superconductor (Li,Fe)OHFeSe, Supercond. Sci. Technol. 35 (2022) 064007,
https://doi.org/10.1088/1361-6668/ac68a9

M. Y. Chen, K. Iida, K. Kondo, et al.
Inter- to intra-layer resistivity anisotropy of NdFeAs(O,H) with various hydrogen concentrations, Phys. Rev. Mat. 6, 054802 (2022), DOI: 10.1103/PhysRevMaterials.6.054802

J. Hänisch, S. Wimbush
Properties of Superconductors, in: J. Rumble (ed), CRC Handbook of Chemistry and Physics, 103rd edition, CRC Press, 2022

J. Hänisch, S. Wimbush
High-Temperature Superconductors, in: J. Rumble (ed), CRC Handbook of Chemistry and Physics, 103rd edition, CRC Press, 2022

Bagrets N., Heller R., Weis J.R., et al.
„Thermal Resistance Between Metallic Surfaces of Copper and Stainless Steel at Different Temperatures and Applied Forces for High Current HTS Cable-in-Conduit Conductors" IEEE Transactions on Applied Superconductivity, (2022) 32 (6), 8800205,
DOI: 10.1109/TASC.2022.3154327

Hohe J., Schober M., Weiss K.-P., et al.
„Verification of Puck's criterion for CFRP laminates under multiaxial loads at ambient and cryogenic temperatures" Composites
Science and Technology (2022), 228, 109631,
DOI: 10.1016/j.compscitech.2022.109631

Santillana I.A., Vallone G., Anderssen E., et al.
„Mechanical Characterization of Low-Carbon Steels for High-Field Accelerator Magnets: Application to Nb3Sn Low-β Quadrupole MQXF" IEEE Transactions on Applied Superconductivity (2022), 32 (6), 4100507,
DOI: 10.1109/TASC.2022.3149853

Nickel D.S., Bagrets N., Fietz W.H., et al.
„Subscale HTS Fusion Conductor Fabrication and Testing in High Magnetic Background Field" IEEE Transactions on Applied Superconductivity (2022) 32 (4), 4200907,
DOI: 10.1109/TASC.2022.3151581

Tirunilai A.S., Weiss K.-P., Freudenberger J., et al.
„Revealing the Role of Cross Slip for Serrated Plastic Deformation in Concentrated Solid Solutions at Cryogenic Temperatures"Metals,(2022) 12 (3), 514,
DOI: 10.3390/met12030514

Corato et al.
„The DEMO magnet system – Status and future challenges" Fusion Engineering and Design,(2022) 174, 112971 , OI: 10.1016/j.fusengdes.2021.112971

Weiss K.-P., Hetzler S, Kvackaj T., et al.
"Cryogenic material properties of additive manufactured 316L stainless steel", IOP Conf. Series: Materials Science and Engineering, 1241 (2022) 012047 ,
doi:10.1088/1757-899X/1241/1/012047

Heiduk, M.; Wolf, M. J.; Fietz, W. H.
Reel-to-reel fabrication of HTS CroCo Strands and Test of HTS CroCo Demonstrator Coils
2022. IEEE Transactions on Applied Superconductivity, 32 (4), Art.-Nr.: 4800805.
doi:10.1109/TASC.2022.3152985

Wolf, M. J.; Fietz, W. H.; Heiduk, M.; et al.
200 kA DC Busbar Demonstrator DEMO 200 – Conceptual Design of Superconducting 20 kA Busbar Modules Made of HTS CroCo Strands
2022. IEEE transactions on applied superconductivity, 32 (4), 1–5. doi:10.1109/TASC.2022.3152130

## Proceedings

S.I. Schlachter, J. Brand, S. Elschner et al.
"Test of a DC-HTS Busbar Demonstrator for Power Distribution in Hybrid-Electric Propulsion Systems for Aircraft"
CEC/ICMC 2021, July 19-23, 2021, virtual
IOP Conf. Series: Materials Science and Engineering 1241 (2022) 012037
doi:10.1088/1757-899X/1241/1/012037

Fink S., Fuhrmann U., Zwecker V.
Cryogenic testing of a 25 kV RIS bushing
CEC/ICMC 2021, July 19-23, 2021, virtual
IOP Conf. Series: Materials Science and Engineering 1240 (2022) 012148
doi: 10.1088/1757-899X/1240/1/012148

S. Fink, R. Müller and V. Zwecker
Cryogenic high voltage testing of a 25 kV RIS bushing
2022 IEEE International Conference on High Voltage Engineering and Applications (ICHVE), 2022,
pp. 1-4,
doi: 10.1109/ICHVE53725.2022.9961329.

M. Yazdani-Asrami, S. M. Seyyedbarzegar, A. Sadeghi, et al.
„High temperature superconducting cables and their performance against short circuit faults: current development, challenges, solutions, and future trends"
Superconductor Science and Technology vol. 35, no. 8 (2022), p. 083002.
doi: 10.1088/1361-6668/ac7ae2.

## Presentation

S.I. Schlachter, N. Bagrets, M.B.C. Branco et al.
Development and Test of High-Temperature Superconductor Harness for Cryogenic Instruments on Satellites
Applied Superconductivity Conference 2022, October 22–28, 2022, Honolulu, USA

Fink S., Müller R., Zwecker V.
Cryogenic high voltage testing of a 25 kV RIS bushing
IEEE International Conference on High Voltage Engineering and Application (ICHVE'22), virtual, 25.9.-29.9.2022

Sonja I. Schlachter, Joerg Brand, Steffen Elschner et al.
"DEMO200 – First steps towards a superconducting 200 kA DC busbar demonstrator"
Applied Superconductivity Conference 2022, October 22-28, 2022, Honolulu, USA

M. J. Wolf & T. Arndt
Wasserstoff und Supraleitung
ZIEHL VIII, Berlin, 5. April 2022

T. Arndt
Energy & Material Efficiency: Liquid Hydrogen & HTS – a perfect fit
Konferenz CIMTEC, Perugia, Italien, 23.06.2022

T. Arndt
Linking the Energy Vector "Liquid Hydrogen" to Power Engineering – HTS as an enabler
Konferenz HTS4FUSION, 29.06.2022, Karlsruhe

T. Arndt
Liquid Hydrogen – Transport, Storage & Usage in Power Engineering
Zentrum Energie, Wasserstoff-Woche, Triangel, 30.06.2022, Karlsruhe

T. Arndt
Magnet Infrastructure (of KIT)
Konferenz Test Facilities for Superconducting Magnets, INFN-LASA, Mailand, 17.11.2022

T. Arndt
Status and Prospects for Superconducting Power Systems
Konferenz ISS 2022, Tsukuba, Japan und virtuell, 29.11.2022

Michael Wolf
AppLHy! – Transport and Application of Liquid Hydrogen (LH2)
TransHyDE- wissenschaftliche Konferenz, Berlin, 30.11.2022

S. Palacios
How Hybrid Pipelines Tackle Multiple Challenges in the Energy Transition
TransHyDE- wissenschaftliche Konferenz, Berlin, 30.11.2022

S. Palacios
How Hybrid Pipelines Tackle Multiple Challenges in the Energy Transition
Ideenwettbewerb „Energie und Umwelt Meine Idee für morgen"
Stiftung Energie & Klimaschutz, Stuttgart, 25.11.2022

## Posters

Q.H. Pham, M. Noe:
"Experimental investigation of the switching behavior of high-temperature superconductors with an alternating magnetic field",
Applied Superconductivity Conference 2022, October 22-28, 2022, Honolulu, USA

Sonja Schlachter, Marcus Collier-Wright, Manuel La Rosa Betancourt et al.
"A Magnetohydrodynamic Entry System for Space Transportation (MEESST)"
Applied Superconductivity Conference 2022, October 22-28, 2022, Honolulu, USA

M. Wehr, M. J. Wolf, T. Arndt
Combined Large-Scale Transport of Chemical and Electrical Energy – Design of a Hybrid Energy Transfer Line with LH2 and High Temperature Superconductors
Helmholtz-Workshop, Frankfurt, 30.05.2022

M. Wehr, M. J. Wolf, T. Arndt
AppLHy! – Conceptual Designs of hybrid Energy Pipelines (LH2 + HTS) – Experimental Studies on the Influence of the thermal Coupling of HTS Wires and Cryogen
ASC 2022, Honolulu, USA, 21.10.2022

Barth, A. Ballarino, A. Devred et al.
Onset of Mechanical Degradation due to Transverse Compressive Stress in Nb3Sn Rutherford-Type Cables K. Puthran, C. ASC 2022, Honolulu, USA

S. Fatehi, A. Bernhard, S.C. Richter, et al.
Validating a HTS miniature, periodic quadrupole driving a short length transport line for laser-plasma accelerators
ASC 2022, Honolulu, USA

# Energy System Design (ESD)

## Book essay

De Carne, Giovanni; Liserre, Marco; Wald, Felix;
"Smart transformer control of the electrical grid" Advances in Power System Modelling, Control and Stability Analysis. Ed.: F. Milano, p.451-471, 2022,
doi: 10.1049/PBPO217E_ch13

## Journal article

G. De Carne; Lauss, Georg; Syed, Mazheruddin H.et al.,
„On Modeling Depths of Power Electronic Circuits for Real-Time Simulation – A Comparative Analysis for Power Systems"
IEEE Open Access Journal of Power and Energy, vol. 9, pp. 76-87, 2022,
doi: 10.1109/OAJPE.2022.3148777.

G. De Carne, A. Morandi and S. Karrari,
„Supercapacitor Modeling for Real-Time Simulation Applications"
IEEE Journal of Emerging and Selected Topics in Industrial Electronics, vol. 3, no. 3, pp. 509-518, July 2022,
doi: 10.1109/JESTIE.2022.3165985.

Shahab Karrari, Giovanni De Carne, Mathias Noe,
"Adaptive droop control strategy for Flywheel Energy Storage Systems: A Power Hardware-in-the-Loop validation" Electric Power Systems Research 212 (2022) 108300,
doi: 10.1016/j.epsr.2022.108300.

S. Karrari, N. Ludwig, G. De Carne et al.,
„Sizing of Hybrid Energy Storage Systems Using Recurring Daily Patterns"
IEEE Transactions on Smart Grid, vol. 13, no. 4, pp. 3290-3300, July 2022,
doi: 10.1109/TSG.2022.3156860.

T. Jacob, A. Buchholz, M. Noe et al.
Comparative Life Cycle Assessment of Different Cooling Systems for High-Temperature Superconducting Power Cables
IEEE Transactions on Applied Superconductivity, vol. 32, no. 4, pp. 1-5, June 2022, Art no. 4802805
doi: 10.1109/TASC.2022.3168239.

## Proceedings

G. Arena, D. Vinnikov, A. Chub et al.,
„Accuracy Analysis of Dual Active Bridge Simulations under Different Integration Methods"
2022 AEIT International Annual Conference (AEIT), Rome, Italy, 2022, pp. 1-6,
doi: 10.23919/AEIT56783.2022.9951711.

F. Ashrafidehkordi and G. De Carne,
„Improved Accuracy of the Power Hardware-in-the-Loop Modeling using Multirate Discrete Domain"
2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems
(PEDG), Kiel, Germany, 2022, pp. 1-5,
doi: 10.1109/PEDG54999.2022.9923128.

Buticchi, Giampaolo; De Carne, Giovanni; Pereira, Thiago et al.
"A Multi-port Smart Transformer for Green Airport Electrification"
24th European Conference on Power Electronics and Applications (EPE ECCE Europe 2022), Hanover, Germany, 05.09.2022–09.09.2022; Publisher: IEEE, ISBN 978-9-0758-1539-9, 2022

M. Courcelle, D. Kottonau and G. De Carne,
„Synchronized Micro-Controllers-based Data Acquisition System for Energy Plants using Modbus Protocol" 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2022, pp. 1-7,
doi: 10.1109/ECCE50734.2022.9948022.

G. De Carne and D. Kottonau,
„Power Hardware In the Loop laboratory testing capability for energy technologies"
2022 AEIT International Annual Conference (AEIT), Rome, Italy, 2022, pp. 1-5,
doi: 10.23919/AEIT56783.2022.9951766.

De Carne, Giovanni; Liserre, Marco; Wald, Felix;
Smart transformer control of the electrical grid
Advances in Power System Modelling, Control and Stability Analysis. Ed.: F. Milano, p.451-471,
doi: 10.1049/PBPO217E_ch13

Ö. Ekin, G. Arena, S. Waczowicz, et al.
Comparison of Four-Switch Buck-Boost and Dual Active Bridge Converter for DC Microgrid Applications
2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems
(PEDG), Kiel, Germany, 2022, pp. 1-6,
doi: 10.1109/PEDG54999.2022.9923074.

P. Emiliani, A. Blinov, A. Chub, et al.,
Black Start and Fault Tolerant Operation of Isolated Matrix Converter for dc Microgrids
IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, 2022, pp. 1-5,
doi: 10.1109/IECON49645.2022.9968735.

P. Emiliani, A. Blinov, A. Chub, et al.,
DC Grid Interface Converter based on Three-Phase Isolated Matrix Topology with Phase-Shift Modulation,
2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems
(PEDG), Kiel, Germany, 2022, pp. 1-6,
doi: 10.1109/PEDG54999.2022.9923256.

Q. Tao, Qiucen; Geis-Schroer, Johanna; Wald, Felix et al.,
The Potential of Frequency-Based Power Control in Distribution Grids,
2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Kiel, Germany, 2022, pp. 1-6,
doi: 10.1109/PEDG54999.2022.9923112.

# Invited Papers

**Katharina Battes**

- K. Battes, Outgassing rate studies and Monte Carlo simulations, DPG Meeting 2022, Regensburg, 4–9 Sept. 2022

**Christian Day**

- Chr. Day, Deuterium-Tritium fuel cycle: Overview and DEMO objectives, IAEA Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy, Vienna, Austria, 11–13 Oct 2022.
- Chr. Day, Overview of tritium designs and developments for European DEMO, 13th Int. Conf. On Tritium Science and Technology, Bucharest, Romania, 16–21 Oct 2022

**Stefan Hanke**

- S. Hanke, Experimental characterisation of a NEG pump of novel size – a major step to its application in neutral beam injectors of future fusion devices, DPG Meeting 2022, Regensburg, 4–9 Sept. 2022.

**Jens Hänisch**

- J. Hänisch, Recent Developments in Fe-Based Superconductors – Towards Understanding Their Vortex Matter and Possible Applications, invited talk, MRS Spring Meeting, 24.05.22, online

**Bernhard Holzapfel**

- Tailored High Tc Superconductors for Power and Magnet Applications MSM Conference, Duisburg, 31.8.2022
- HTSC Coated Conductors for Power and Magnet Applications ITC31 Conference, virtuell, 9.11.2022
- Tailored High Tc Superconductors for Power and Magnet Applications: nm defects for kA on the km scale Walther-Meißner-Seminar, Garching, 2.12.22

**Jonas Schwenzer**

J.C. Schwenzer, EU-DEMO fuel cycle operation modelling and design, IAEA Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy, Vienna, Austria, 11–13 Oct 2022.

**Christos Tantos**

- C. Tantos, Transient modeling of the gas flows in the gas injection systems of fusion reactors, DPG Meeting 2022, Regensburg, 4–9 Sept 2022.

**Tim Teichmann**

- T. Teichmann, Direct Simulation Monte Carlo of diffusion pumps for the application in fusion reactors, DPG Meeting 2022, Regensburg, 4–9 Sept 2022.

**Stylianos Varoutis**

- S. Varoutis, Particle exhaust and vacuum pumping on ITER and other devices, IAEA Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy, Vienna, Austria, 11–13 Oct 2022.

**Klaus-Peter Weiss**

- Weiss K.-P., „Structural material challenges for fusion magnets“, Symposium on Fusion Technology SOFT 2022 Dubrovnik, Invited Talk

# Patents Held

- 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
  FR 3256359
  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.
  CH 3335228
  CN 10814458
  DE 3335228
  DE 102015010636.8
  FR 3335228
  GB 3335228
  IE 3335228
  US 10825585

- Verbinder für supraleitfähige Leiter und Verwendung des Verbinders
  Fietz, Walter; Heller, Reinhard; Weiss, Klaus-Peter; Wolf, Michael J.
  CH 3335280
  CN 10814961
  DE 3335280
  DE 102015010634.1
  FR 3335280
  GB 3335280
  IE 3335280
  US 10218090

- Verfahren und Vorrichtung zur Herstellung eines supraleitfähigen Leiters
  Fietz, Walter; Heller, Reinhard; Weiss, Klaus-Peter; Wolf, Michael J.
  CN 10814715
  DE 102015010676.7
  EP 16756943.3-1212
  US 11328841

- 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
  WO PCT/EP2021/025312

- Bandleitervorrichtung und Kabel, das die Bandleitervorrichtung aufweist
  Arndt, Tabea
  DE 102020128417.9
  WO PCT/EP2021/078897

- Hochtemperatur supraleitende Schaltvorrichtung
  Martz, Simon; Noe, Mathias; Pham, Quoc Hung
  LU LU502329

- Hochtemperatur supraleitender Schalter
  Noe, Mathias
  LU LU502334

- Modular High Capacity Current Lead
  Wolf, Michael J.
  US 63/278,850

# 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**
Dr. Holger Neumann (-22625)

**Superconducting and Cryomaterials**
Prof. Dr. Bernhard Holzapfel (-26000)

**Energy Applications**
Prof. Dr.-Ing. Mathias Noe (-23500)

**Administration**
Kai Bauer (-23705)

**Superconducting Magnet Technology**
Prof. Dr. Tabea Arndt (-23515)

**Fusion Fuel Cycle Technologies**
Dr. Christian Day (-22609)