Karlsruher Institut für Technologie

ITEP – Institute for Technical Physics

Progress in Research and Development
2012 Annual Report

INSTITUTE FOR TECHNICAL PHYSICS

KIT – University of the State of Baden-Wuerttemberg and
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Contents

Preface

The Institute for Technical Physics (ITEP) is a national and international competence center for fusion, superconductivity, and cryogenic technologies. Activities focus on the following areas:

- Technology for fusion magnets.
- Tritium process technology.
- Vacuum technology.
- Cryoengineering.
- Development of superconductor materials and applications of superconductivity in power technology.
- Superconducting high-field magnets.

The work of ITEP is part of the "Fusion", "Efficient Energy Conversion and Use", and "Astroparticle Physics" long-term programmes of the Karlsruhe Institute of Technology (KIT) and Helmholtz Association of National Research Centres.

The complex and, in most cases, multi-disciplinary tasks are accomplished by ITEP in large, unique experimental installations, laboratories, and technical infrastructure facilities. These are:

- The Karlsruhe Tritium Laboratory (TLK), a worldwide unique laboratory with a closed tritium cycle for civil purposes.
- The Karlsruhe Toroidal Coil Test Facility (TOSKA) for testing large magnets for fusion and for developing components for future fusion reactors.
- The test facility for the ITER Model Pump (TIMO) for the development of cryo-vacuum pumps.
- High-field Magnet Laboratory for developing superconducting high-field magnets.
- The Cryogenic High-voltage Laboratory for investigating high-voltage stability of cryogenic insulation materials.
- The Cryogenic Material Laboratories for studying electric and mechanical properties at very low temperatures.

In 2012, the year of its 35th anniversary, the Institute for Technical Physics – as in the previous years – achieved remarkable scientific results and mastered specific challenges that will be summarized briefly below.

In the fusion **magnets field**, ITEP develops, builds, and tests high-current leads with high-temperature superconductors for the Wendelstein 7-X fusion project. In 2012, the last series-type current leads were tested successfully at currents of up to 20 000 amperes and accepted according to schedule. Moreover, the first project phase in the construction and supply of high-current leads for the JT60-SA project was completed successfully by supplying the materials agreed upon. For the ITER fusion experiment (www.iter.org), the Division executed a number of cryogenic mechanical materials tests.

Within the framework of the ITER international fusion experiment, the **Karlsruhe Tritium Laboratory (TLK)** is to supply the work packages for water detritiation (WDS) and cryogenic isotope separation (ISS). In 2012, the combined WDS-ISS test facility was tested with all process control units and safety-relevant installations. Several analytical methods for tritium determination in water and in the liquid hydrogen phase were further developed. Moreover, exchange of the process control system was continued with a minimum outage duration of the components affected. Measurement systems for radiation protection were replaced in close cooperation with the KIT Safety Management Service Unit.

The **Vacuum Technology Division** of ITEP focuses on the development of vacuum systems of extremely high pumping capacity. In 2012, the built-to-print design of the cryopump for the ITER neutral particle heating system was completed. In addition, a new reference concept was developed for the fuel cycle of future fusion power plants to ensure the higher flow rates required, while the inventory of substances involved is minimised. Work on the development of the necessary metal foil pumps started. A new facility was set up and commissioned successfully for the highly precise measurement of outgassing of materials.

In the **development of superconductor materials**, development of economically viable low-loss conductor concepts suited for high currents represents a major task. Work in 2012 focused on the further development and characterization of HTS Roebel cables. Using a Roebel cable developed by KIT, a transport current of 12 000 amperes was measured in CERN at a magnetic field of 6 tesla and a temperature of 4.2 kelvin. As regards the **applications of superconductivity in power technology**, first promising tests started at a new test facility for the characterization of AC losses under a joint project for the development of a superconducting cable of 1 km length and 40 MVA. The development of a new high-performance current limiter component for a European cooperation project was completed successfully.

Work of the **High-field Magnet Laboratory** focuses on the development of high-field NMR systems with high-temperature superconductors. In 2012, the first milestone of a cooperation project with industry was reached. The second project phase was continued. It was found that the extraordinarily high material requirements defined are fulfilled in principle by HTS tape conductors of the second generation. For the description of anisotropy of the critical current density in magnetic fields, mathematical models were developed and verified by measurements.

The **Cryoengineering Division** develops, extends, and operates complex, large-scale cryosystems, among others for the KATRIN tritium neutrino experiment or the CuLTKa current lead test facility. Both facilities were developed further to a considerable extent. Supply of major KATRIN-related experiments with cryogen was ensured. In addition, this Division is in charge of repair and maintenance of cryogenic facilities and of supply of KIT with liquid helium and liquid nitrogen. A European joint project for the development of superconducting wind power generators was started with the Cryoengineering Division assuming a major share in the work.

Within the **Karlsruhe Tritium Neutrino Experiment** KATRIN (www.katrin.kit.edu), ITEP makes major contributions to the tritium loops, cryogenic supply, and superconducting magnets. Large parts of the concept for the rear section of KATRIN were developed. Experiments were performed to successfully demonstrate the feasibility of activity monitoring of the source by X-ray detectors. A project highlight in 2012 was the successful and highly precise calibration of the laser Raman method for tritium analysis.

As **regards changes of staff**, the number of staff members undergoing training and advanced education, such as students of cooperative state universities, diploma students, doctoral students, and trainees continued to increase. In total, more than 50 persons are undergoing training in various disciplines at ITEP.

In the field of **teaching**, more lectures were newly conceived and introduced. In 2012, ITEP staff offered lectures in the amount of 22 hours per week per semester for KIT students. In addition, numerous national and international seminars, summer schools, and workshops were organised by ITEP. In November 2012, ITEP co-organised the high-ranking conference "Coated Conductors for Applications" with nearly 120 participants from 15 countries at Heidelberg.

The celebration of the 35th anniversary of ITEP in July 2012 was combined with the traditional summer party. I am very grateful to all helpers and participants.

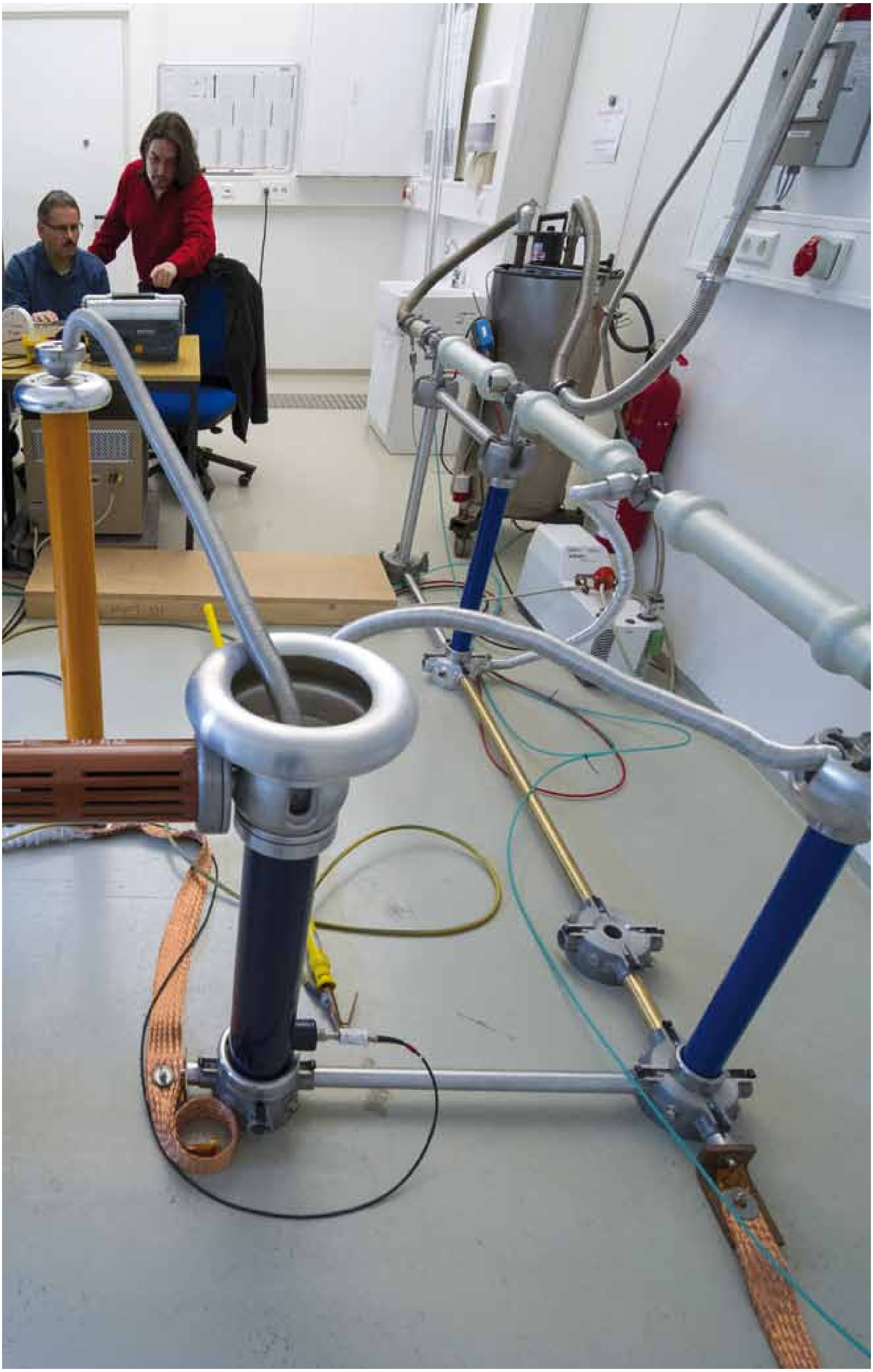
In 2012, some **very high honours** were granted to ITEP members: Dr. Franceso Grilli was awarded the Dr. Meyer-Struckmann Science Prize for his excellent work on and scientific contributions to modelling superconductors in June 2012 by BTU Cottbus. Dr. Klaus-Peter Weiss was accepted for the Helmholtz Academy of Executives. I am very pleased about these honours and would like to congratulate cordially on this success!

Awarding of the Dr. Meyer-Struckmann Science Prize of BTU Cottbus to Dr. Francesco Grilli (right).

I would like to express my cordial thanks to all partners of ITEP from universities, research institutions, and industry for the very loyal, fruitful, and successful cooperation in 2012.

Sincerely yours,

Mathias Noe



Test of room temperature high-voltage prototype breaks for ITER, fabricated by Babcock-Noell.

Results from the Research Areas

Fusion Magnets

Head: Dr. Walter Fietz

ITEP is engaged in the field of fusion magnets and supports the national project W7-X and the international projects ITER and JT-60SA. In addition basic research is performed with respect to future magnet technology.

Construction of current leads for W7-X and JT-60SA

Work for Wendelstein 7-X

ITEP has developed, constructed and tested 16 current leads for the plasma experiment Wendelstein 7-X (W7-X) with a maximum current of 18.2 kA. Two prototypes and 14 series current leads were equipped with Bi-2223 High Temperature Superconductors leading to a significant reduction of the required cooling power.

After the successful test of the prototype current leads and the consecutive approval of the manufacturing of the series current leads in 2010, the fabrication started.

Fig. 1: Test cryostat connected to TOSKA
a) Closed
b) Open with view to the connection between the current lead and the bus bar.

In 2012 the manufacturing continued and was completed in October. Acceptance tests have been successfully performed for 6 current lead pairs in a test cryostat which was attached to the TOSKA main vacuum vessel (Figure 1); the test of the last series pair has been prepared. All results obtained so far show reproducible good results.

Work for JT-60SA

Based of the experience at ITEP in the area of HTS-current leads the BMBF committed in 2007 that KIT shall deliver current leads for the satellite tokamak JT-60SA. The outline data were formally agreed between EU and Japan in 2009 and signed in 2010. Afterwards ITEP did the conceptual design of the current leads.

In 2011 the interfaces were mutually agreed and fixed together with F4E and Japan and the design was frozen. In 2012 ITEP worked on the detailed design (Figure 2). Bases are the results of the W7-X prototype current leads test. The approval of the authority TÜV was achieved and the detailed design completed. Afterwards the procurement of materials and components started.

Fig. 2: CAD-model of the 26-kA-current lead for JT-60SA.

Current Lead Test Facility CuLTKa

For the acceptance test of the 26 current leads for JT-60SA a new facility CuLTKa (Current Lead Test facility Karlsruhe) is under construction and needs to be integrated in the cryogenic infrastructure of ITEP. CuLTKa ensures a higher test frequency compared to the series tests at TOSKA which is required to assure the completion of the project within the required schedule. The manufacturing of the different cryostats and valve boxes is in progress. All cryostat boxes have been fabricated and are now under installation (Figure 3). The delivery of the LN2-shields is delayed by about six months due to quality problems during the fabrication at the company. In 2012 the cryo-transfer lines were ordered in industry and are presently under fabrication. The connection of CuLTKa to the existing cryo infrastructure can only start after the completion of all tests for W7-X because TOSKA cannot be operating during the connection work.

The manufacturing of the series current leads for W7-X and the consecutive acceptance tests have been completed in 2012. In 2013, the test of two repaired current leads will be performed. Afterwards the fabrication of the 26 series current leads for JT-60SA will start and the test facility CuLTKa will be completed and commissioned. The project “current leads for JT-60SA” will run until begin of 2017.

Support of ITER

In case of a fast discharge of a large magnet high voltages occur which depend on the magnet inductance and the time constant which is allowable to retract the stored energy from the magnet. As a consequence ITER

Fig. 3: Construction of the cryo infrastructure of the test facility CuLTKa.

needs high voltage instrumentation feedthroughs to route voltage and sensor lines from the magnets that are positioned in the vacuum of a cryostat to the data acquisition. To have sufficient safety margin ITER did ask for pluggable instrumentation feedthroughs that can withstand voltages of 56 kV DC and 35 kV AC. In addition it was requested that the insulation must withstand high voltages even under Paschen conditions (10-4 mbar to almost ambient pressure) which is extremely demanding because under such pressure condition breakdown can occur already at voltages of some 100 volt.

Because ITEP had already developed high voltage feedthroughs that were used for testing of the ITER Toroidal Field Model coil TFMC, ITER asked ITEP to develop together with industry pluggable high voltage feedthroughs.

Starting with the TFMC-feedthrough design of ITEP, a design was developed with the Otto-Dunkel GmbH (ODU), Mühldorf that included the industrial production skills of ODU. ODU finally fabricated 4 feedthroughs (Fig. 4) that had to undergo intensive vacuum and high voltage testing at ITEP. These feedtroughs passed all tests and were finally accepted by ITER.

In another ITER contract ITEP examined room-temperature high voltage breaks that allow a leak tight connection of He-pipes that deliver Helium to the superconducting magnet system, but offer an electrically disconnection. In earlier experiments low temperature breaks were successfully tested but room temperature breaks showed unclear results.

The new experiments have shown that under the typical ITER He flow of ITER 4.5 g/s the breaks were within the specification given by ITER. However, for stagnant Helium the HV strength.

Fig.4: Socket (left) and plug (right) of the high voltage feedthrough.

Fig. 5: Room temperature high voltage break during testing.

Cryogenic material tests and mechanical Tests of superconducting cables (CryoMaK laboratory)

Mechanical measurements

Beside the increasing number of tasks in the framework of the ITER project to qualify structural materials, several request from industry outside the „Fusion" program were processed. The spectrum of mechanical characterization ranged e.g. from properties of adhesive foils (Figure 6) to friction stir welding of aluminum plates at cryogenic temperatures for space applications.

In superconducting applications structural requirements are important, but also thermal characterization is relevant. Therefore, dedicated samples of high temperature superconductor tapes were made. Here, additionally to the thermal conductivity in tape direction, the transversal conductivity was determined. Copper stabilized tapes from Superpower were used. Fully copper coated tape samples as well as samples with polished sides, removing the thermal copper short cut via the tape edges, were measured. These types of samples are very challenging due to the extreme short measurement length or thickness, partly compensated by the stacking of tapes (Figure 7). Results exhibit that the thermal conductivity in tape direction is of three magnitudes higher than transversal direction. Additionally using different types of samples an arithmetic verification of the qualitative results were achieved (Figure 8).

Fig. 6: Peeling test (180°) and tensile test (0°) of an Al-adhesive tape at 4.2K.

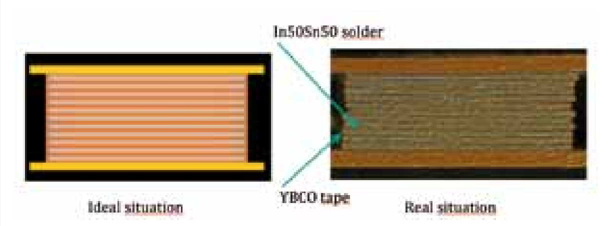


Fig. 7: Cross sectional area of an HTS stack to measure the thermal conductivity (red – copper).

Because of the increasing inquiry regarding the expertise of cryogenic material tests, the CryoMaK laboratory is now part of the Helmholtz Energy Materials Characterization Platform (HEMCP). Coordinated by FZJ together with DLR, HZB, HZDR and KIT this collaborative project proposal succeeded, aiming to provide necessary scientific infrastructure to characterize and develop functional and structural materials under extreme conditions within the frame of energy technology.

HEMCP will be installed from 2013 to 2016. Due to the various characterization methods of the participating associations an extraordinary long termed platform is established to support energy research.

Measurements of the FBI facility

After upgrading of the FBI facility successfully to measure the critical current Ic in applied magnetic field B using a variable temperature insert (4.2 – 80 K), already last year a first measurement of an HTS Roebel cable was performed.

Because of the unique test possibilities of the FBI facility further alternative HTS cable concepts were investigated (Figure 9). Successful measurements of the robust Conductor on Round Core (CORC) cable provided by Advanced Conductor Technologies were conducted. This cabling concept uses 15 tapes, wound in five layers around a central former – in this case a conventional copper power cable (Figure 10). Further investigations will show the scalability by adding further layers of superconducting tapes.

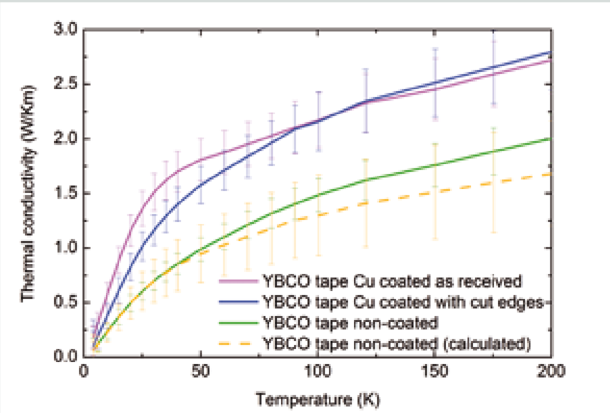


Fig. 8: Results of the thermal conductivity measurement – fully coated with copper (as received), removed copper side (with cut edges), without copper coating (non copper), calculated from copper coated subtracting copper contribution (calculated).

Fig. 9: Dr. Makoto Takayasu of the Massachusetts Institute of Technology/USA (left) and Dr. Danko van der Lann of Advanced Conductor Technologies and University of Colorado/USA (right), each during the test of a HTS cable in the FBI facility.

Another conductor candidate measured is the Twisted Stacked Tape Cable realized by MIT. A stack of 40 tapes was soldered into a copper tube for electrical stabilization. A special method to contact the single HTS-YBCO tapes electrically was used. These were alternately clamped between BSCCO tapes to allow an extreme low resistance. The Ag matrix of the BSCCO tapes can be soldered easily into a copper block to be contacted to the current lead of the test facility. The clamp can be opened to change the cable under test.

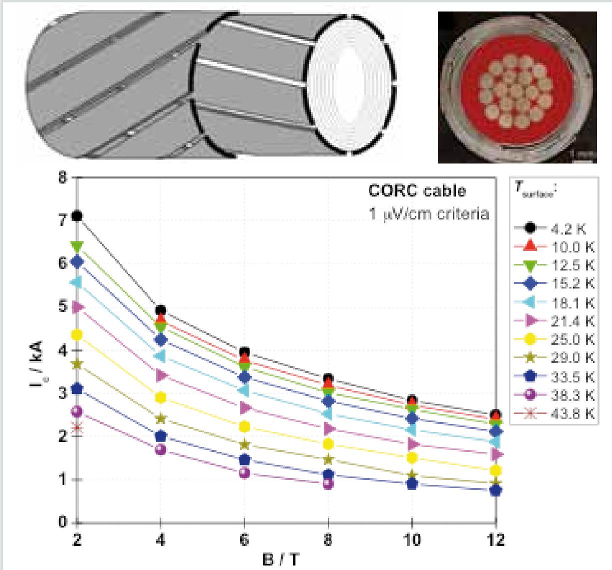


Fig. 10: I_c (B,T) results obtained from the HTS-CORC cable.

Highlight 1: Tests of the HTS current leads for Wendelstein 7-X

Fig. 11: Series manufacturing of the current leads for W7-X.

All series current leads are fabricated in KIT until mid-2012 (Figure 11). Until October 2012 six current leads pairs for W7-X were successfully tested. The tests have been conducted using a coordinated test program and cover heat load measurement without current, current tests at 14 kA and 18.2 kA, 6-hours test at 18.2 kA, and loss of helium flow simulation tests. All current leads achieved the design values for all parameters:

- The heat load at 4,5-K level were measured to be (2.1±1) W and the 50 K He mass flow rate at a current of 18.2 kA was 1,38 g/s (Figure 12).
- The temperature margin was measured to be more than 25 K which ensures enough margin for the operation in Wendelstein 7-X.
- In case of a loss of helium flow accident at 18.2 kA it takes about 18 minutes until a quench occurs in the HTS module of the current leads (Figure 13).
- The measured pressure drop in the heat exchanger is fully in agreement with the CFD modeling (Figure 14).

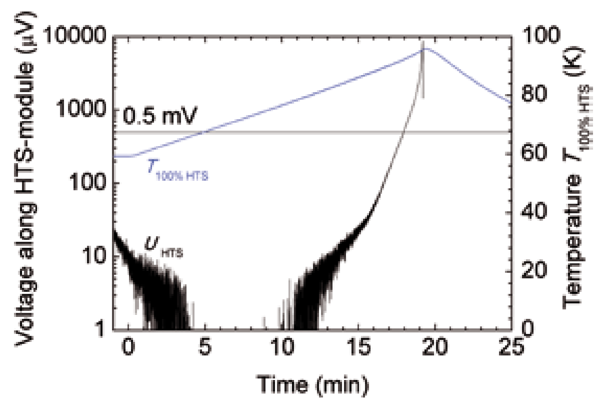


Fig. 13: Voltage across the HTS module and temperature rise at the warm end as a function of time during the loss of helium mass flow simulation at 18.2 kA.

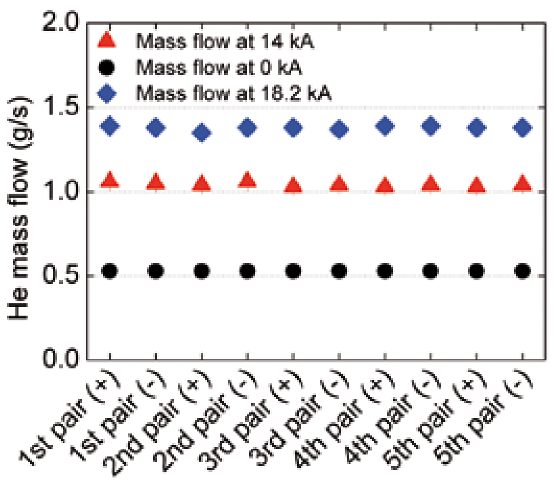


Fig. 12: 50 K Helium mass flow rate through the heat exhanger measured fort he series current leads 1 – 10.

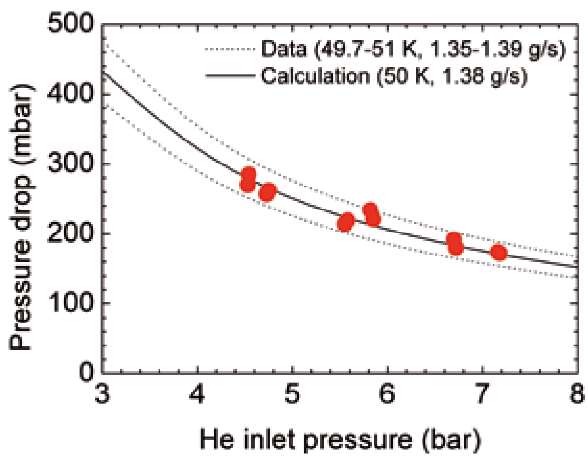


Fig. 14: Pressure drop in the heat exchanger at room temperature as a function of the helium mass flow rate.

Highlight 2: Development of pluggable high voltage feedthrough for ITER

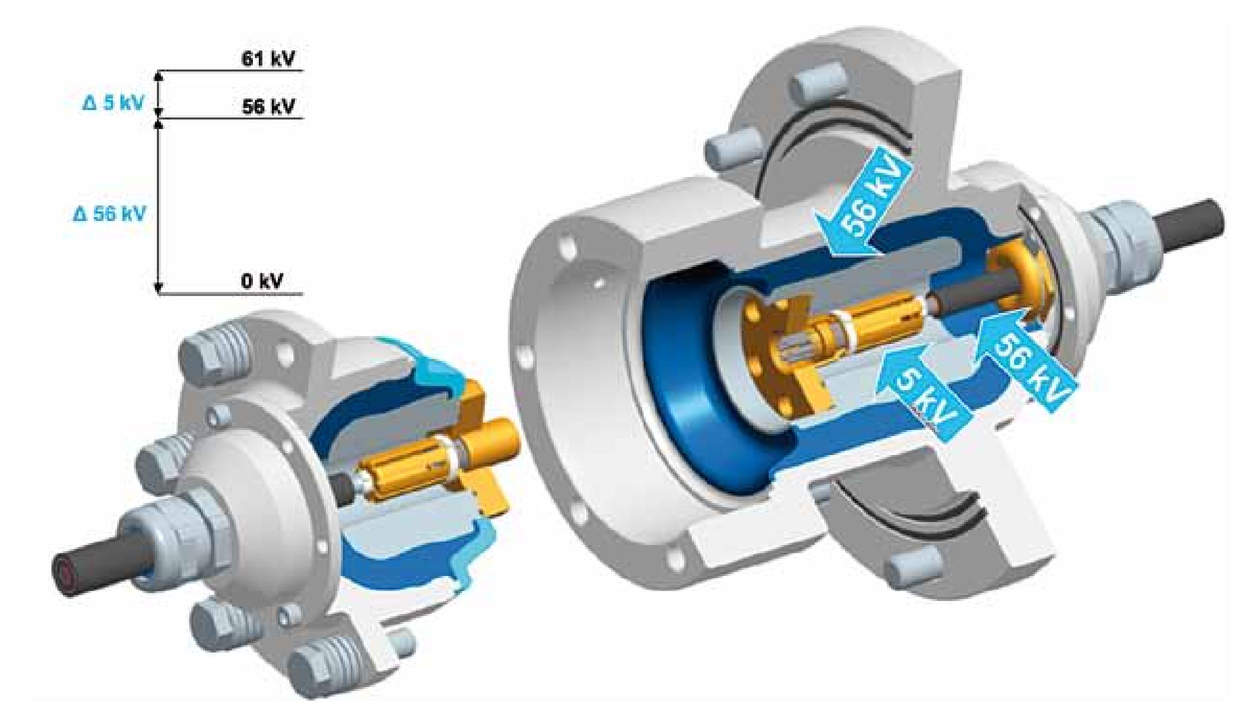


Fig. 15: detail view of high voltage feedthrough for ITER.

For ITER pluggable high voltage feedthroughs are necessary to route signals from voltage taps or sensors from the cryostat vacuum to the data acquisition.

To have enough margin ITER defined a maximal test voltage of 56.000 V DC or 35.000 V AC for the feedthrough.

KIT developed in collaboration with Otto-Dunkel-GmbH Mühldorf (ODU) such pluggable feedthroughs. ODU fabricated in an industrial process 4 feedthroughs that were tested in KIT under following conditions:

- 35 kV DC 5 min in air
- 35 kV(peak) AC 5 min in air
- 35 kV DC 1 min in steps under Paschen conditions
- 56 kV DC 5 min in air

All feedthroughs passed these tests. The design allows an industrial fabrication in series.

Fig. 16: HV feedthrough (CAD-Design).

Fig. 17: Connected socket and plug of the HV feedthrough.

Technical Centre of the Superconducting High Field Magnet group: Production of a copper solenoid for a superconducting current limiter with inductive resistive coupling.

Results from the Research Areas

Superconducting High-field Magnets

Head: Dr. Theo Schneider

The work of the Superconducting High Field Magnet group in 2012 covered R&D for the expansion of HOMER II, the NMR project with the Bruker BioSpin GmbH Company and cooperation with the Institute for Synchrotron Radiation (ISS). Tests of FGB-sensors and coil production, e.g. for a mixed cryostat from Professor Alexey Ustinov from the Physical Institute (PI) were also included. These projects encompass a variety of technical applications, so that the superconductor implemented fulfils complex and multifaceted requirements.

The scientists assessed amongst other things: low field optimised NbTi and $(NbX)_3Sn$ superconductors for undulator windings, the first commercial MgB_2 conductor used for a superconductor energy storage in the field range from 2 – 5 T, reinforced $(NbX)_3Sn$ conductor in a field range of 12 – 15 T, high current $(NbX)_3Sn$ conductor for a field of around 20 T and modern REBCO high temperature superconductor for the high field range of greater than 24 T.

Industrial Cooperation – NMR-Projects

NMR Magnet Technology

In intensive long-standing collaboration with the company Bruker BioSpin GmbH, the ITEP is developing novel superconducting high field magnets for the partner's high resolution NMR spectroscopy, and supports them in launching the product worldwide and in its quality assurance. For more than fifteen years, researchers have been testing commercial technical superconductors within the NMR magnet technology project set up for this purpose, and qualifying them by means of high resolution E(I) measurements in the JUMBO and HOMER I facilities. The superconductors under investigation vary from one another in their manufacturing processes, material composition, dimensions and physical characteristics which lead to a multitude of test configurations. As well as the superconductors, the scientists also characterised the superconducting joints made from the conductors and optimised their rest resistivity in the pΩ range, dependent on the external magnetic field. The results of the experiments and their evaluation are cooperation know-how and therefore confidential.

1 200 MHz NMR-Project

The aim of this ambitious NMR project is to develop an NMR-qualified HTS insert coil for building an NMR spectrometer with a proton resonance frequency of approximately 1200 MHz. Unlike other HTS projects of the ITEP, the HTS will be operating here at temperatures lower than 4.2 K instead of 77 K. Therefore the fundamental properties of the conductor at lower temperatures must be determined (see figure 1). More about this is described in the highlights paragraph.

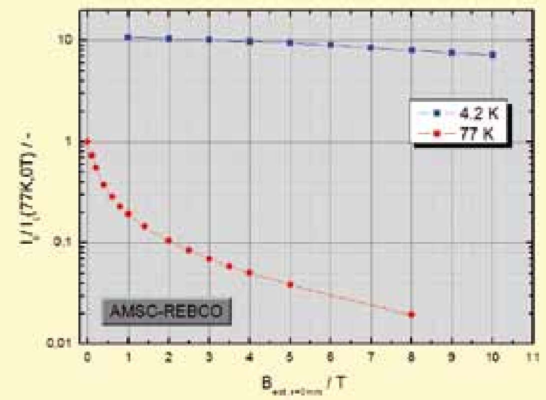


Fig. 1: I_c(B) dependency of an AMSC REBCO conductor at 77 K and 4.2 K.

EuCARD

EuCARD (European Coordination for Accelerator Research and Development) is a joint project of 37 European partners. The main goal of EuCARD is the development of innovative concepts and technologies for an upgrade of the biggest European research accelerators such as the Large Hadron Collider (LHC). The current accelerator magnets of the LHC are designed for a magnetic field of 8.3 T. The magnets are wound from NbTi superconductor and operated at 1.9 K. For the planned upgrades of the LHC, HL-LHC (High Luminosity-LHC) and HE-LHC (High Energy-LHC) magnet systems in the region of 13-20 T are required. Therefore a working package of the EuCARD projects comprises the development of new magnet technology on the basis of $(NbX)_3Sn$ and high temperature superconductors.

For the HE-LHC, a 2-3 times increase in the energy value is necessary; i.e. dipole magnets are required that can produce a flux density of 20 T. The present dipole design would provide a 14 T LTS-background magnet system, consisting of NbTi and NbSn coils, and a 6 T HTS insert magnet.

At the beginning of the project Bi2212 conductor wire and REBCO conductor tape were available as conductor material for the HTS insert coil. Due to the reduced critical current density, limited strength and complex coil production process by the W&R method, the scientists decided against the Bi2212 conductor and are concentrating on the REBCO conductor.

The KIT High Field Group is involved in the superconductor characterisation and tests of HTS solenoid windings within the EuCARD project.

Fig. 2: Experimental set-up for characterising a REBCO double pancake in line with the EuCARD project.

After some delay, at the end of 2011 one of the first REBCO double pancakes produced by the French project partners CNRS was delivered to the ITEP. A 4 mm wide REBCO band from the company SuperPower with 10 layers per individual pancake was used in the production. The experimental E(I) analysis of the double pancakes was carried out in the 15 T magnet configuration of the HOMER I experimental facility. Figure 2 shows the fully equipped double pancake used in the HFL next to the innermost 15 T NbSn coil from HOMER I. The team carried out various constructive adaptations in order to guarantee a secure test assembly. The U(I) characterisation was carried out in a parallel magnet configuration with potential taps for quench detection and an additional compensation coil for noise reduced U(I) determination. In the first step the double pancake coil was tested in the range of the expected load current of the conductor. For this the coil was loaded with a transport current of up to 400 A at magnetic fields of between 8 and 12 T. These tests, by which a maximum hoop stress of 500 MPa acts on the conductor, were successfully carried out. In a second step, the critical current I_c was to be determined. In doing so the REBCO conductor reached its maximum mechanical load at a magnetic field of 10 T and a transport current of 698 A (corresponding to a hoop stress of 730 MPa) and broke through at the start of the windings. A similar result – wire break at 700 MPa – was obtained by our partner CNRS whilst measuring on a similarly constructed double pancake. Complex double pancakes and solenoid coils are currently in the construction and test phase at the French partners.

Cooperation within KIT

FBG Sensors

Together with the Cryo-group of the ITEP, the scientists analysed the mechanical strain of a superconducting coil caused by local Lorentz forces with FBG sensors. The

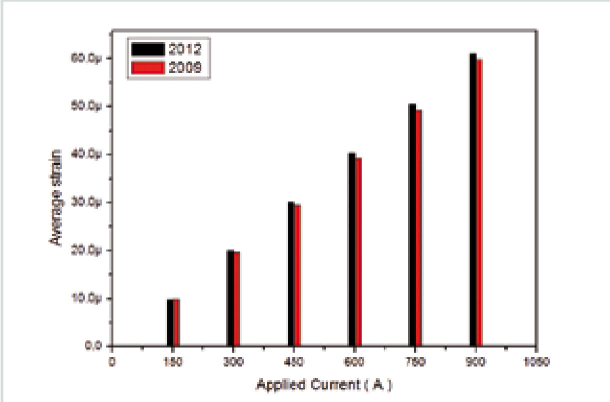


Fig. 3: Comparison of the results of the FBG measurements for 2009 and 2012 carried out with identical measurement equipment.

reproducibility of these measurements is very important; therefore NbTi test coils, already tested in 2009, were measured again in the same way.

Figure 3 shows the measurement results from the years 2009 and 2012 which achieve very good agreement with a deviation of less than 2%. No degradation of the sensors was apparent. For the functioning of the FBG sensors during superconducting coil operation, it must be shown that the measurements recorded are independent of the cause of the strain. To this end, the sensors were tested in three different operational modes: firstly with constant magnetic field, varying the transport current; secondly with constant transport current, varying the magnetic field; and thirdly by loading a coil with simultaneously varying magnet field and transport current. The researchers were able to prove the independence of the strain generation, and therefore the reproducibility.

Coil production

The team built a copper solenoid that will be used as a primary coil in a laboratory demonstration of a superconducting current limiter with inductive resistance coupling to support the dissertation work of O. Näckel. A small copper coil with 2800 windings was developed for Professor Mathias Noe as a test inductance for his lecture. Professor Alexey Ustinov's group at the PI required an external magnetic field for the analysis of the spin transition of the rare earth ion Erbium. The experiment was carried out at 20 mK in a Helium-mix cryostat so that the external magnetic field could only be achieved with a superconducting coil. The group constructed a coil using a thin 0.18 mm NbTi round conductor with which interesting results have been produced.

LIQHYSMES

Within this project, the coils of the superconducting energy storage (SMES) should be wound from commercial MgB_2 superconductor. In order to determine the $I_c(B)$ behaviour of the MgB_2 conductor, the group began the first pre-tests in simple test geometries in LHe.

Component Production

A key question for coil design and magnet operation is the behaviour of the superconductor when subject to the Lorentz force. The HFM team assesses this routinely by means of U(I) measurements on a threefold coil set

Fig. 4: Braiding machine in the technical centre for producing the copper braids for the current lead.

which for the 15 T configuration of the HOMER I experimental facility consists of coils with diameters of 150 mm, 80 mm and 40 mm. The coil set is connected to a quadruple current lead that was configured to deliver 300 A per terminal. As the current transport capability of the commercial REBCO high temperature superconductor is far above 500 A at 15 T, the quadruple current lead had to be renewed for the determination of the maximum Lorentz force load of the REBCO conductors. Naturally the new current lead had to be suited to the existing structure of the magnetic system whereby the maximum current of the current lead cannot be arbitrarily increased. The redesign resulted in a current carrying capability of c. 750 A per terminal. For each terminal a bundle of six woven copper braids were wrapped in a steel tube and welded on to the current lead head. The woven copper braids consisted of 32 copper wires wound around a central copper core. The braids were manufactured on the braiding machine in the group's technical centre as shown in figure 4.

An optimal copper type with a low specific resistance at low temperatures should be used for the copper braids as well as for the current carrying components of the other test objects used by the group. Therefore the team determined the specific resistance of various commercially available types of copper at room temperature, 77 K and 4.2 K (see figure 5).

For this, the copper was tested not only in its delivered condition, but also after heat treatment (e.g. 2 h at 700° C). Oxygen free (OF) copper showed the best results with a 100 times lower specific resistance at 4.2 K than standard copper; therefore this was used for the copper braids. After welding and gluing, the vacuum group tested the leakage rate of the finished assembled terminals of the current lead. After assembly was complete, the HFM-team determined the flow rate of the entire current lead. The new current lead is in place; the electrical connection of the threefold coil set is finished; the system is ready for testing.

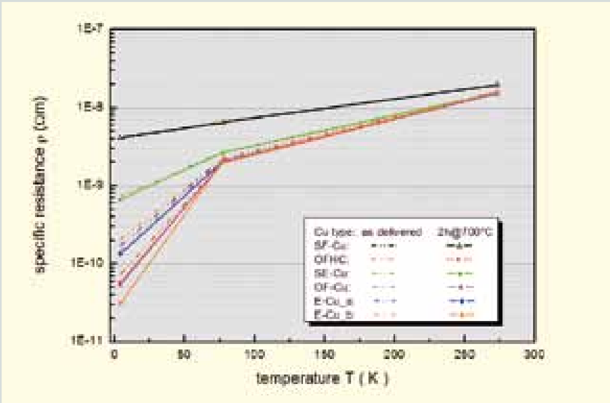


Fig. 5: Temperature dependent specific resistance of commercial copper materials.

Highlight: 1 200 MHz NMR Project - First milestone achieved

The project, which began on 1st October 2010 with a duration of five years, is split into three project phases. The results of each phase are appraised at a milestone date whereby the continuation of the project is decided. The first project phase was complete at the end of March this year. The project partners fulfilled the demanding requirements of the first milestone and are continuing with the project.

The emphasis of the first project phase was on a comprehensive E(I) characterisation and, in principle, the high-field qualification of the commercially available REBCO HTS coated conductor at liquid helium temperature with a background magnetic field of 20 T. A worldwide market analysis showed that in the corresponding time period three out of four companies were already able to deliver REBCO test conductor in long enough lengths without normal conducting soldered joints and produced with a satisfactory I_c homogeneity. Figure 6 shows the construction principle of the four potentially suitable REBCO conductor types.

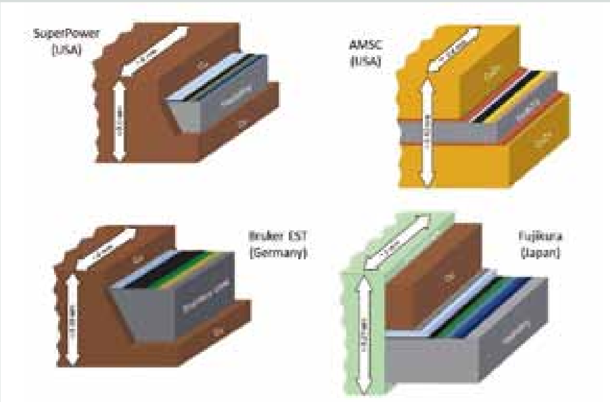


Fig.6: Construction of the REBCO conductor.

High resolution NMR spectroscopy puts high demands on the superconducting coil system; the main coil system must demonstrate a relative spatial homogeneity of the central magnetic field $\Delta B/B_0$ in the ppm range in order to reach the required resolution of 2 Hz. In addition, the time stability of the field must be maintained with a drift rate of less than 10 Hz/h. These requirements can only be fulfilled if the researchers test the electromagnetic and thermo-mechanic properties of the REBCO conductor in a variety of test configurations.

For E(I) characterisation of the technical superconductor, the HFM group has available a diverse range of test objects for short probes, test coil bodies with diameters from 33 mm to 250 mm with variable lengths and winding layers, as well as special objects from coil technology. The appraisals are carried out in the experimental facilities of the High Field Laboratory (JUMBO and HOMER I) in magnetic fields up to 20 T at liquid nitrogen (77 K) and liquid helium temperatures (4.2 – 1.8 K), and transport currents of up to 3000 A. The scientist must be aware whilst carrying out the tests that the high transport currents can lead to premature normal conducting, (quenching) and the associated destruction of the REBCO.

Initially the magnet designer is interested in is the dependence of the critical current and the n-value on the applied magnet field and temperature. The main question of whether the chosen superconductor in a magnetic field of 28.2 T can withstand the transport current under the Lorentz force existing in the windings must be answered by means of experiment and extrapolation using mathematical models. The REBCO coated conductors from the three commercial suppliers were therefore carefully tested in special test configurations. Throughout the project, the anisotropic behaviour of the REBCO's has become more and more important.

I_c Anisotropy

In order to determine the anisotropic behaviour of the critical current I_c of the REBCO conductor, angle-dependent measurements of the resistive transition properties in the angle range $\Phi = 0 – 90°$ in an external magnetic field at LHe and LN_2 temperatures were necessary. For this, the team built a new probe holder for the JUMBO experimental facility that can carry a current of up to 1500 A and have an angular setting of up to $\pm \Delta \Phi = 1°$ (see figure 7).

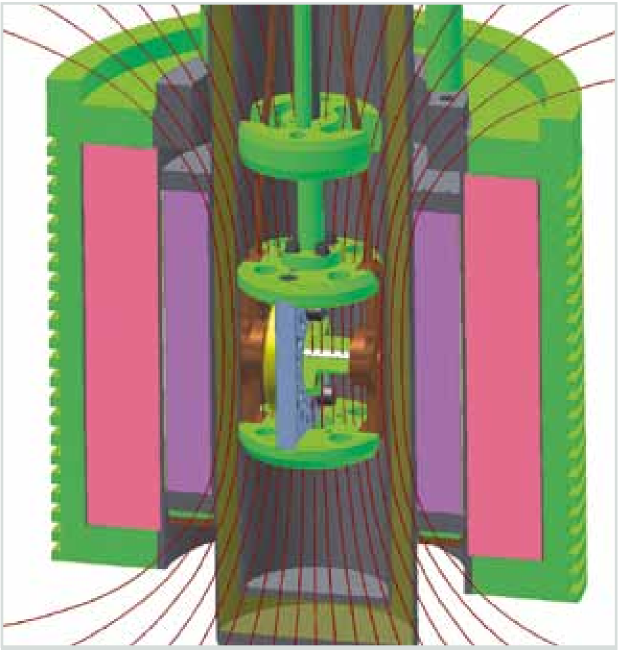


Fig. 7: Rotating sample holder for determination of the $I_c(B,\Phi)$ surface at 77 K.

The scientists experimented with a 4 mm wide, copper laminated SuperPower conductor, an approximately 5 mm wide Fujikura conductor and two 4.4 mm wide AMSC conductors (with steel and brass laminate respectively). The U(I) measurements were carried out using the four-point measurement method in which the external JUMBO magnetic field at 4.2 K was varied from 0 – 10 T. The superconductor was loaded with a current of up to 1500 A, corresponding to the maximum present capacity of the test configuration. At 77 K the behaviour of the conductor could only be measured up to approximately 6 T because in the region of B_{c2}, the current carrying capability was less than 1 A.

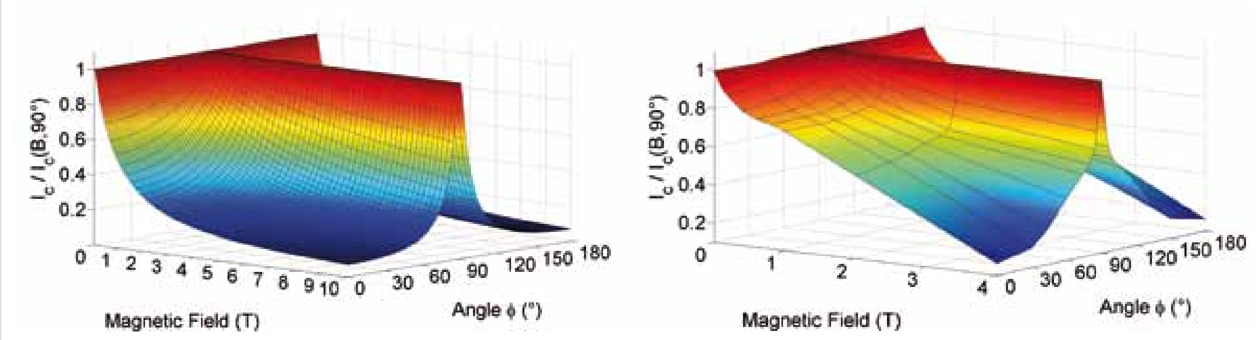


Fig.8: ***$I_c(B, \Phi)$ surface (normalised to $I_c(B, 90°)$ value) at 4.2 K (left) and 77 K (right) for the AMSC conductor with steel laminate.***

The U(I, B, T, Φ)-characteristic curves were evaluated by means of a power law and the I_c value was thus determined. The $I_c(B, \Phi)$ surfaces were fitted with the Matlab Curve Fitting Toolbox using an I_c function based on the theory from Kim modified with an anisotropy function according to Blatter. Thereafter the function was extrapolated to the operating region of 30 T. To represent the four coated conductors tested, the $I_c(B, \Phi)$ surfaces (normalised to $I_c(B, 90°)$ value) for the steel laminated AMSC conductor at 4.2 K and 77 K are illustrated in figure 8.

Figure 9 shows the extrapolated $I_c(B, \Phi)$ surface of the brass-laminated AMSC conductor up to 30 T.

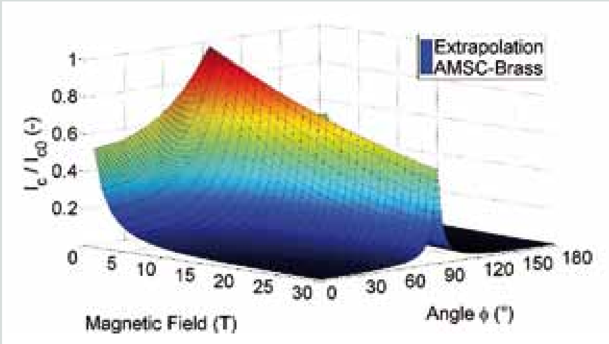


Fig. 9: Extrapolation of the $I_c(B, \Phi, 4.2K)$ surface for a brass laminated AMSC coated conductor.

Model of a power cable for the AMPACITY project; partial fitting with superconducting tapes (inner phase).

Results from the Research Areas

Superconducting Materials and Applications in Power Technology

Head: Dr. Wilfried Goldacker

Superconductor development

In 2012, superconductor development at ITEP concentrated on low-loss REBCO tape conductors and on high-current cable systems made of these tape conductors, such as Roebel cables and Rutherford cables. They are considered for use in future transformers, rotating machines, and high-field magnets (e.g. for fusion). In addition, stranded conductors of magnesium diboride wires were manufactured and tested for AC applications.

HTS AC conductors

Low-loss types of the REBCO tape conductor require a filament structure. Using an innovative IR laser of ITEP, this structure was burned into the layer set-up. Up to 160 parallel lines were produced on a conductor width of 12 mm (see Fig. 1). The theoretically predicted reduction of losses was confirmed by loss measurements. Decrease of transport current with the number of filaments was slightly higher than the expected value, which is to be attributed to conductor inhomogeneities. Higher losses were identified to be due to irregular current-carrying capacities (inhomogeneities) of the material. These inhomogeneities are caused by conductor manufacture.

The optimized piko-second laser (funded by the BMWi under grant FKZ0327489B) can be used to cut 18 – 25 microns wide channels into the layer structure without melting effects (see Fig. 2). The method was applied successfully to the most common layer architectures, including copper cap layers. Process parameters were defined.

Fig. 1: Filament structure burned into a REBCO tape conductor by a laser beam, with 10, 20, and 40 filaments, respectively, on a conductor width of 12 mm.

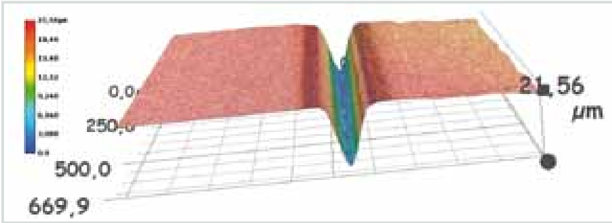


Fig. 2: 3D-processed microscopy of a lasered ditch of about 21 microns in depth.

Micro undulators

This project is carried out by ITEP in cooperation with ANKA, the KIT synchrotron radiation source. Under the project, a periodic meandering current path was cut into a tape conductor layer in order to generate a periodic self-field along the centre of the conductor. The periodic field profile along the conductor was verified by measuring the magnetic field using a Hall probe in ANKA. The structure can be used as a micro undulator, whose field can be increased by stacking tape conductors of identical parallel structure. This is the first system of its kind worldwide.

Low-loss HTS high-current conductors

Low-loss Roebel cables based on punched REBCO tape conductors were produced with average sample lengths of about 5 metres (see Fig. 3). Universal end contacts allowed for a systematic investigation of pancake and layer windings using a single cable sample. Winding distance in both arrangements was changed in a stepwise manner in order to characterise mutual influence of adjacent cables. The pancake winding is shown in Fig. 4. The Roebel cable used survived a large number of assembly modifications without any degradation. For the pancake design, 2D FEM modelling calculations were made. In the input data, complex inho-

Fig. 3: Roebel cable made of a REBCO tape conductor of 5 m length, 10 strands, and 12 mm width.

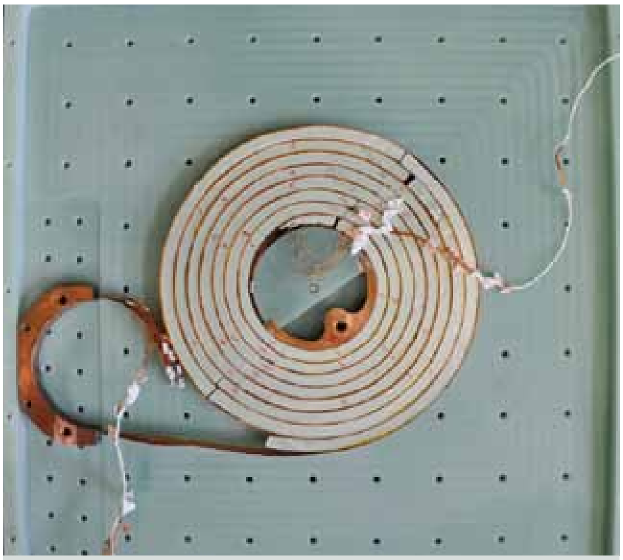


Fig. 4: Pancake winding of a 5 m long Roebel cable with variable spacers in the package (view from above).

mogeneous conductor properties were considered, such as anisotropic and unsymmetric current distribution in magnetic fields. The calculated transport currents were somewhat higher than the measured values. This was attributed to manufacture-induced conductor inhomogeneities.

Figure 5 shows a Rutherford cable equipped with three Roebel strands for future application in large generators or fusion magnets. Current-carrying capacity of the strands was measured, AC losses were determined.

Fusion and ITER

Structural materials for cryogenic use have to possess a well-defined behaviour under mechanical loading at cryogenic temperature. The quality of the material is determined by its fracture behaviour and the correlated microstructure. The microscopy team analysed tensile specimens by electron microscopy in order to characterise their fracture behaviour. Based on the fracture pattern, it can be decided whether a ductile or brittle fracture exists, which is important for cryogenic use. The specimens studied were made of structural material used in the ITER work programme.

Fig. 5: CAD design of a Rutherford model cable equipped with three Roebel strands for current measurement.

Applications in power engineering

In the field of applications of superconductivity for power engineering, ITEP contributed to numerous projects. First studies of the current-limiting superconducting transformer, which is a project performed in cooperation with industry, were carried out. Work was executed for a European project to produce a current limiter and ITEP contributed to a superconducting power cable for urban application. Activities were complemented by studies of superconducting wind energy generators under a PhD thesis entitled "Efficient superconducting equipment and renewable energy."

Fault current limiter

The ECCOFLOW project funded by the EC is aimed at developing a superconducting current limiter for the medium-voltage range based on the second generation of high-temperature superconductors (REBCO tape conductors) with two applications in the power grid. For this project, ITEP, in cooperation with the industry partner NEXANS Superconductors, developed the current limiter component that is arranged in a stack and connected in series with the other units. An innovative insulation method developed by KIT for long superconductors and novel spacer tapes were incorporated in industrial series production. The component was measured and qualified in terms of its switching properties. After the high-voltage test at ERSE in Milan, the current limiter will be applied in the grid of the Spanish utility Endesa on the island of Mallorca and then in a transformer station near Kosice/Slovakia. After reliable operation, it will presumably be subjected to a long-term test in a real grid.

Fig. 6: Model of the power cable in liquid nitrogen.

Fig. 7: Partial view of the power cable with the inner phase in the contact area.

Power cable based on high-temperature superconductors

Under the AMPACITY project funded by BMWi, the so far longest superconducting power cable of about 1 km length is being developed, manufactured, and integrated in the grid of the city centre of Essen by the RWE-NEXANS-KIT consortium. Integration will be completed by 2014. Under this project, ITEP studies the losses and complex excitation states to be expected in practical operation of the cable. The model cable has a length of about 2 m. As regards the position of the superconductor, the geometry is identical to that of the power cable. Cooling takes place in a nitrogen tub of 3 m length (see Fig. 6). Figure 7 shows the contact area of the cable in detail.

Computer simulations with special further developed software are of crucial importance. They allow for a two- or three-dimensional description of the electric states of the cable for the future advanced design of such cables.

In a first phase, the model cable was equipped with a superconducting layer (phase 1) in a stepwise manner. Physical properties were measured and correlated with model calculations. An advanced 2D model was found to be qualified for a sufficiently correct description of the cable.

Superconductivity in space research

When space shuttles re-enter the atmosphere of the earth, a plasma layer forms around the shuttle. It shields electromagnetic radiation, disrupts radio communication (black-out), and heats up the surface of the spacecraft. Magnetic fields of sufficient strength can displace this plasma layer. Superconducting magnets can reach highest field strengths. In cooperation with DLR and IOFFE, St. Petersburg (Helmholtz-Russia Joint Research Project), ITEP develops and constructs an HTS magnet for a shielding test in the DLR plasma channel. ITEP has already produced and successfully tested first small magnets based on REBCO tape conductors. The magnet will be applied in the plasma beam in the DLR plasma channel and, hence, requires a special cryostat construction and cryotechnology. In addition, ITEP contributes model calculations of the deflection of charged plasma particles.

Fig. 8: The Baden-Wuerttemberg Minister of the Environment, Climate Protection, and the Energy Sector, Franz Untersteller, visits the superconducting power technology laboratory of ITEP and speaks with Dr. Wilfried Goldacker (ITEP) about potential use of superconductivity for the integration of renewable energies and efficient energy use within the framework of the transformation of the energy system.

Highlight
Roebel strands of the Rutherford cable

Strands of Roebel cables of 4 mm width are envisaged for use in the Rutherford model cable. First activities concentrated on studying the current-carrying capacity of the strands after assembly. The central carrier around which the strand is arranged has a small radius of curvature. Hence, the strand is subjected to bending. To study the bending effects, the bending behaviour was analysed systematically in the continuous edge bending strain rig (CEBRS) of KIT (see Fig. 9). By means of this set-up, the transposition angle can be increased gradually and the superconducting critical current can be measured to determine the degradation limit while the conductor is bent.

Figure 10 shows the results of bending tests performed at two curvature radii of 10 and 15 mm and two cable orientations, i.e. internal superconducting layer (red) and external superconducting layer (black). A vertical line at a transposition angle of about 19 deg. gives the angle of the cable structure. An internal superconductor was found to be more advantageous, as degradations were smaller. However, 5% loss of ampacity have to be expected for the stranded Roebel cable according to measurements.

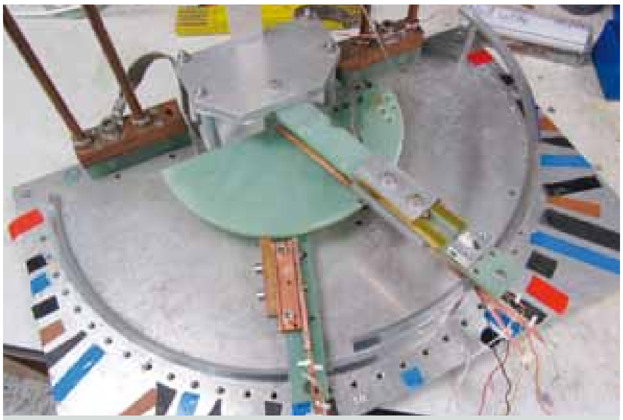


Fig. 9: Continuous edge bending strain rig for measuring the bending behaviour of conductors and cables.

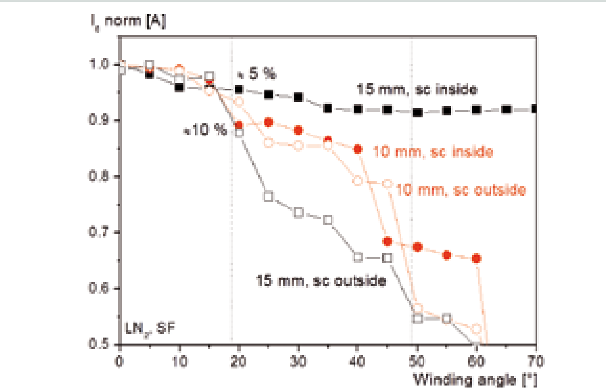


Fig. 10: Critical current of Roebel strands during bending in the CEBSR for an internal and external superconducting layer and two curvature radii of 10 and 15 mm.

Roebel pancake

Field distribution of the densely wound Roebel cable (Fig. 11) was modelled using a FEM method (see Fig. 12). Distribution of critical currents over the winding package was determined (see Fig. 13). According to the model, the self-field of the coil reduces transport current from originally 1108 A (design value 1512 A) in the straight cable to 558 A in the coil. Due to conductor inhomogeneities, an even smaller value of about 465 A was measured. As a whole, modelling was found to provide for a good description of the arrangement.

Fig. 11: Pancake winding of a Roebel cable without winding distance.

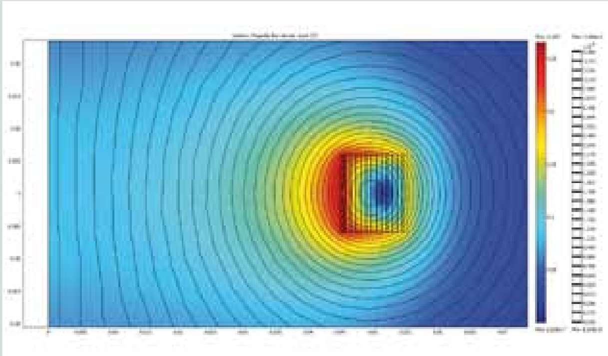


Fig. 12: Modelling of field distribution in the winding package.

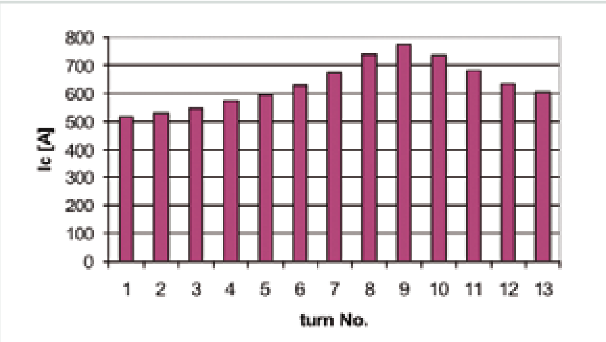


Fig. 13: Modelled currents in the winding layers.

Model power cable for the AMPACITY project

The model cable was equipped with a first-phase winding package consisting of 22 conductors. For comparison, every second conductor was replaced by a dummy to study differences in the cable behaviour. Theoretical predictions were confirmed impressively by both modelling and measurement. Smallest losses are reached by a narrow arrangement of current-carrying tapes. Figure 14 shows the end of a model cable equipped with conductors and dummy tapes. Figure 15 presents the central section of the cable core. Modelling of the currents in a cable section is shown in Figure 16.

Fig. 15: Central part of the cable with 50% superconductor equipment (inner phase).

Fig. 14: End section of the power cable model.

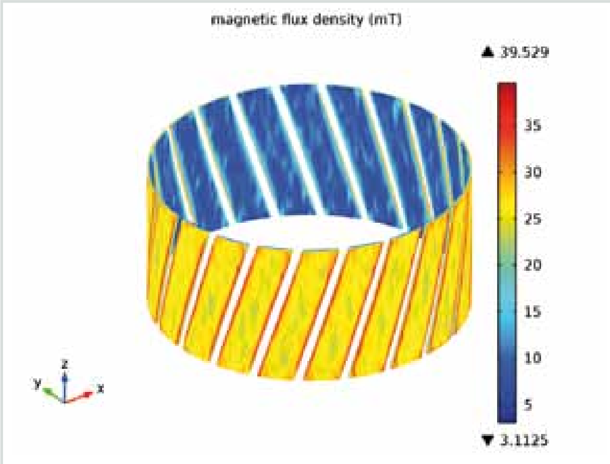


Fig. 16: FEM 3D modelling of currents in the inner phase of the cable.

Processing of molecular sieves in the AMOR facility.

Results from the Research Areas

Tritium Laboratory Karlsruhe (TLK)

Head: Dr. Beate Bornschein

The Tritium Laboratory Karlsruhe is a semi-technical experimental facility unique in Europe and America, which possesses the permission to handle 40 g (1.5 x 10^{16} Bq) tritium, 100 kg depleted uranium as well as rubidium and krypton as test emitters for calibration purposes. An experimental area of more than 1000 m^2 accommodates more than 15 glove box systems with a total volume of about 125 cubic metres as enclosures for the experimental setup for tritium. One of research activities of the TLK to date was and is the development of technologies for the fuel cycle of fusion reactors. The second focus lies on the construction of key systems for the Karlsruhe Tritium Neutrino Experiment (KATRIN) measuring the rest mass of the electron antineutrino. Accordingly, the work is embedded in equal shares in the “Fusion” and “Astroparticle Physics” programmes.

Young scientists are very important for the future of TLK. In the past years, TLK attracted an increasing number of students and doctoral researchers by offering interesting research projects (see Table 1). TLK is highly interested in providing young people with excellent and balanced training that does not only cover technical and scientific aspects, but also the various required soft skills.

	2008	2009	2010	2011	2012
Bachelor	1			6	12
Diploma/Master	2	7	9	9	6
PhD	3	4	8	10	10

Table 1: Completed and ongoing theses at TLK.

Hereinafter, activities and results in the fields of TLK operation and infrastructure as well as fusion research and development will be outlined briefly. The KATRIN activities will be covered by a separate chapter.

TLK operation and infrastructure

In 2012, the tritium infrastructures of the TLK were fully available to the research projects conducted under the programmes of “Fusion” and “Astro”. Tritium from the storage system was supplied in particular to the CAPER experimental facility used for both operational tasks, such as the detritiation of waste gases, and research and development as well as to the experiments TriToP and TriReX (see chapter on KATRIN). The CAPER group additionally produced special tritium gas mixtures for other experiments. The requirements made by the authority within the framework of the operation license were always fulfilled. No reportable events occurred.

On November 22, 2012, 5 g of tritium were delivered to TLK. This tritium was purchased to compensate losses due to radioactive decay in the previous years. The current inventory of TLK now amounts to about 23.5 g tritium and is sufficient to run the research projects in the next two years. From 2014, the inventory will have to be increased in order to supply the necessary amount of tritium to KATRIN.

As in the previous year, work of the Automation and I&C Group focused on the replacement of the TLK process control system. Replacement was necessary, as the old Teleperm M system is no longer supported by the supplier and spare parts are no longer available. In the third reconstruction phase, the old automation system AS7 was replaced. This system is used among others to operate the important tritium retention systems of TLK. For this purpose, the already tested rollback strategy was applied: First, the new system was set up in a test rig near the old system. After shutdown of the old system, the new system was connected via distribution cables to the distribution box parallel to the connections of the old system. Then, functional tests were performed. Three days after the connection of the new automation system already were all functions commissioned successfully. After a test phase of four weeks without any complaints or failures, the old system was disassembled completely. The new system was set up, connected, and commissioned at the same position. Parallel to the work on AS7, planning of the exchange of AS6 was completed. It will be the last old system to be replaced in the next year. All activities, including hardware projecting, software development, and functional

Fig. 1: Set-up of the new automation system.

Fig. 2: View into the TRENTA caisson (accessible flue) with the electrolysers and new operation panels.

tests with simulation assemblies, were performed exclusively by staff of the MAT operation group.

Within the framework of a bachelor thesis of a student of the cooperative state university from the MAT group, two control systems made by Rockwell-Automation for the automatic operation of two electrolysers in the TRENTA facility were replaced by Simatic S7 control units. These were visualised and operated via an operator panel each. For this purpose, the programmed logics of the old systems had to be determined and reprogrammed in the new Simatic control units (see Fig. 2).

The outdated radiation protection measurement system, consisting of data acquisition, bus protocol, multiplexer, and Mevis operation station (ambient monitoring), was found to be increasingly susceptible to failures and it was decided that an exchange was inevitable. The new flexible system with a standard protocol and standard components was set up and taken into operation in cooperation with the KIT Safety Management Service Unit (KSM).

Analytics of tritium at TLK

Performing qualitative and quantitative analyses of the six hydrogen isotopologues H_2, HD, D_2, HT, DT, and T_2 as well as other tritiated compounds (such as HTO) is a major prerequisite for handling tritium, thus imposing strict requirements on experimenters and their equipment. As analytical work is of crucial importance to TLK, research and development activities are coordinated and performed across programmes and groups. This year, R&D work concentrated on the following areas:

- Laser Raman spectroscopy of gaseous tritiated hydrogen isotopologues (see KATRIN chapter).
- Beta-induced X-ray spectroscopy (BIXS) of gaseous hydrogen isotopologues and liquid tritiated water (see KATRIN chapter).
- Infrared spectroscopy of liquid hydrogen isotopologues (see Highlight).
- Application of liquid scintillation as inline method to determine tritium concentration of water (see Highlight).

Parallel to the research and development activities, calorimeters, ionization chambers, and gas chromatographs as well as existing calibration methods were further optimized. The above instruments are the backbone of analytics at TLK. They are used regularly and should always be ready for operation. Accordingly, work in 2012 focused on the purchase and subsequent the commissioning (without tritium) of a gas chromatograph suited for measuring hydrogen isotopologues. The instrument is to replace a device that is about 20 years old and will be installed into the corresponding glove box next year. The corresponding technical planning work started in 2012.

R&D for ITER

Current work on the tritium loop of ITER is concentrates on the European contribution "Water Detritiation and Isotope Separation (WDS-ISS)". For this purpose, TLK develops and studies processes of water detritiation and hydrogen isotope separation in the TRENTA facility under the "Fusion" programme. These activities are aimed at obtaining important data for the WDS and ISS systems and, in this way, contributing decisively to the ITER design. The work will be described in the Highlight section of this report.

Blanket and tritium technology

Future fusion reactors, that are planned to be operated with a fuel mix of deuterium (D) and tritium (T), will require so-called blankets. In these breeder blankets, tritium will be generated from lithium by a nuclear reaction. For this purpose, neutrons are used, which originate from the fusion process. The tritium fuel produced in the blanket has to be extracted from the latter as rapidly and completely as possible and then made available for the fusion process. Consequently, the tritium is purged from out of the blanket using purge gas (for example, helium).

In DEMO, the future demonstration fusion power plant, highly efficient technical processes will be required to recover tritium from the breeder blanket. These processes will have to be quick, reliable, and economically efficient. At the same time, tritium inventories will have to be minimised. The current ITER test blanket module (TBM) concepts cannot be transferred to the much larger DEMO blanket. Therefore new concepts are needed for the extraction of tritium from the blanket.

In the past years, TLK contributed considerably to the comprehensive review process of the corresponding systems. Attention focused on the questions of how the tritium extraction process from the blanket can be simplified to make it more reliable and robust and how tritium accounting can be implemented in the blanket process.

In 2012, these studies were continued within the framework of EFDA tasks. Presently, the focus is on the permeation of tritium from the blanket into the primary cooling loop, and further via the heat exchanger (steam generator, see Fig. 3) into the secondary cooling loop and the environment. The maximum tritium permeation into the secondary cooling loop and from there into the environment accepted is about 2 mg per day. A Comparison of this value with the amount of daily bred and process tritium (~ 400 g) shows that permeation will have to be reduced by more than five orders of magnitude. This can only be achieved by a smart combination of permeation barriers, on the one hand, and highly

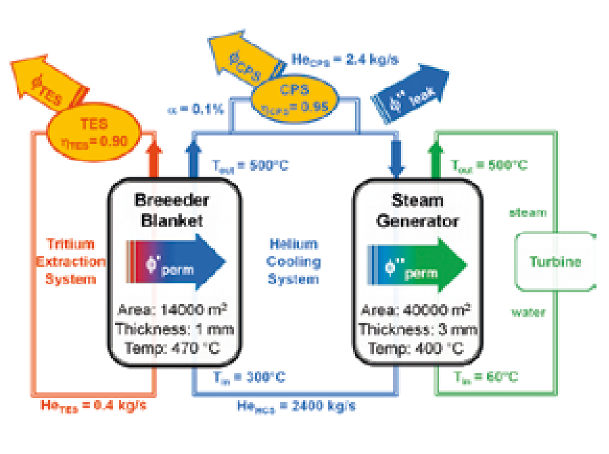


Fig. 3: The tritium permeation problem. The tritium (red) generated in the blanket can permeate into the primary cooling loop (blue) and from there into the second cooling loop (green) and further into the environment.

efficient tritium extraction processes associated with high flow rates in the cooling loop, on the other. An approach to solve this problem is to model of the individual processes.

In cooperation with the KIT Institute of Neutron Physics and Reactor Technology (INR) and a research group of ENEA, Italy, the TLK researchers developed a standardized universal simulation tool for the analysis of various blanket systems. By using this tool, understanding of the process options shall be improved in the next two years. It is the primary objective to develop a blanket concept of maximum efficiency with a minimum tritium inventory, minimum tritium release into the environment, and maximum tritium extraction from the blanket.

Currently, TLK is testing zeolite membranes for their usability in tritium extraction systems. The small facility set up in the past years was extended considerably in 2012 in order to characterise the above membranes under fusion-relevant operation conditions (ternary mixtures of He-H_2-H_2O). First measurement results are expected in 2013.

Parallel to these activities, TLK continued to study the detritiation of highly tritiated water (HTW). One of the first safety studies for ITER emphasised the necessity of installing an additional system for the detritiation of HTW (up to 1.4 MCi/kg). One option consists in detritiation with a membrane reactor (PERMCAT). It is presently being studied by TLK in three steps: First, various concentrations of HTW are generated. Then, the HTW is processed in PERMCAT at variable parameters. The gaseous, tritiated water is detritiated in a counter flow process by isotope exchange with the help of hydrogen.

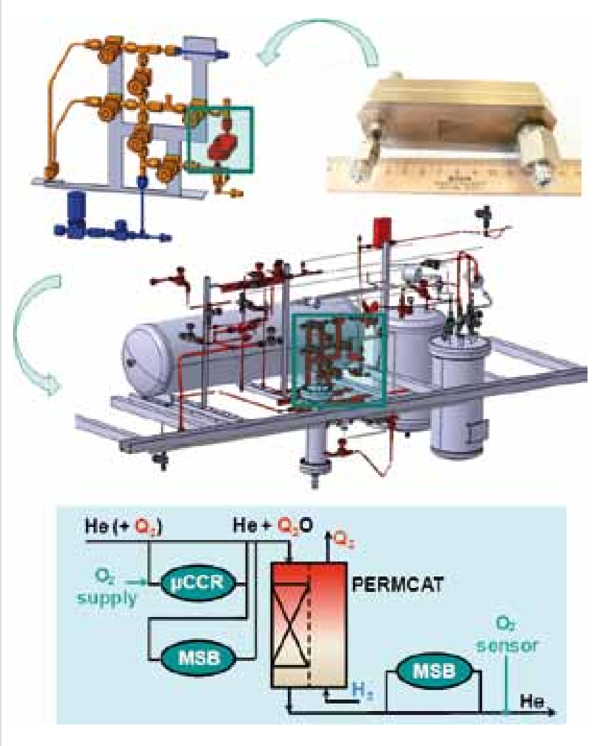


Fig. 4: Experimental set-up for the detritiation of highly tritiated water. The micro-channel reactor µCCR, one of the main components, is located on the top right. The process sketch is shown at the bottom. In the centre, the 3D layout of the CAPER C glove box is represented.

In the first stage that was already introduced in 2009, a metal oxide reactor (MOR) was used to produce highly tritiated water. As the MOR has to be disposed as radioactive waste after use, TLK looked for a more favourable, waste-free solution. It consists in the use of a catalytically based micro-channel reactor (µCCR) developed by the Institute for Micro Process Engineering (IMVT). In 2012, the working group started to extend the CAPER C facility and to connect the micro-channel reactor to PERMCAT, as is shown in the principle flowchart (Fig. 4). Prior to this work, extensive safety analyses were required and performed in cooperation with the Tritium Process Group of TLK. The reason is that tritiated water (HTO) is about ten thousand times more hazardous to man than tritium in molecular form (T_2).

According to present plans, first measurements with relevant tritium concentrations in water will take place in spring 2013.

Highlight:
Water detritiation and isotope separation with TRENTA

If energy is to be produced by fusion power plants in the future, production of large amounts of tritiated water (HTO) cannot be avoided when handling technically relevant amounts of tritium. HTO is produced mainly by the catalytic oxidation of tritiated waste gases in tritium retention systems. ITER already will require a facility for the decontamination of HTO with an activity concentration of 0.4 – 11 TBq kg^{-1} (water detritiation system, WDS) at a flow rate of up to 60 kg h^{-1} HTO. The WDS is of high importance, as it is the last barrier to prevent tritiated waste gases from being released into the environment together with the exhaust gas cleaning system (atmosphere and vent detritiation system). The reference process selected for ITER is based on the so-called combined electrolysis catalytic exchange (CECE). It is tested at the semi-technical TRENTA facility of the Tritium Laboratory.

TRENTA mainly consists of a catalytic separation column operated at about 70°C (LPCE, liquid-phase catalytic exchange column) for isotope exchange between the liquid phase ($HTO_{(liquid)}$) and the gaseous phase (HT, $HTO_{(steam)}$) as well as of two electrolysis cells and one cryogenic isotope separation column operated at 20 K (CD column, cryogenic distillation). By means of electrolysis, tritiated water is decomposed into hydrogen and oxygen. The tritiated hydrogen is fed into an 8 m long LPCE column. At the head end of the LPCE column, fresh water is fed into the system in opposite direction to the hydrogen isotopologs injected into the sump. In this way, tritium is converted from the gaseous into the liquid phase. If the molar ratio between the fresh water and hydrogen isotopologues is smaller than 1, tritium is enriched in the aqueous phase in the swamp of the LPCE column. The tritium-depleted gas flow leaves the LPCE column at the column head. The enriched tritiated water taken from the column swamp is then decomposed by electrolysis again. A partial flow of the tritium-enriched hydrogen can be fed into an about 3 m long cryogenic distillation column via a permeation cell. In the swamp of the cryogenic separation column, a tritium-enriched hydrogen fraction is removed, while the head product is fed into the LPCE column for decontamination prior to release into the environment. Figure 5 shows a strongly simplified scheme of the functioning of TRENTA. Figure 6 shows a view of a plant section.

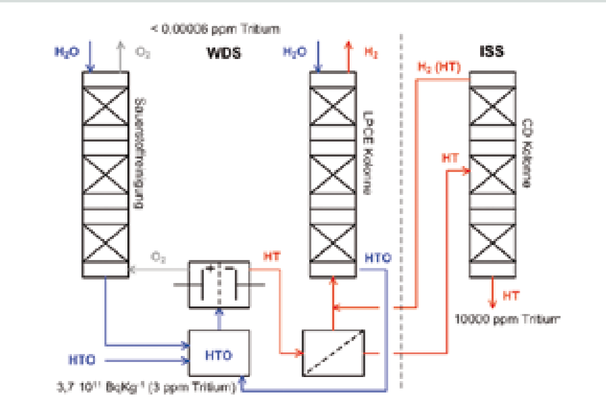


Fig. 5: Simplified scheme of the TRENTA test facility for water detritiation.

Fig. 6: Glove box, valve box, and cryogenic separation column (in insulated tank) of the TRENTA facility (view from above).

The efficiency of the WDS section of the test facility was demonstrated in the past years by parametric studies of TRENTA 3. A decontamination factor of 2.5 x 10^5 was determined experimentally for tritium in water. In 2012, the WDS section and the CD section of the TRENTA facility were combined in TRENTA 4 and taken into operation. This combined operation will be of high importance to tritium retention and water recycling in future fuel cycles of fusion reactors. After extensive functional testing of the combined facility, a leak test, and tests of I&C and safety-relevant functions, followed by a test of all process components for correct installation and functioning, test operation started.

During test operation, an electrolysis cell with tritiated water of 5 x 10^9 Bq kg^{-1} specific activity and a deuterium fraction of 26% was applied. The tritiated hydrogen produced was fed into the LPCE column at 1 m^3 h^{-1}. Simultaneously, the CD system processed a 1 : 1 mix of D_2 and H_2 continuously injected from gas cylinders. The head product of the CD column was fed into the LPCE column at half of its height and processed. Gas samples

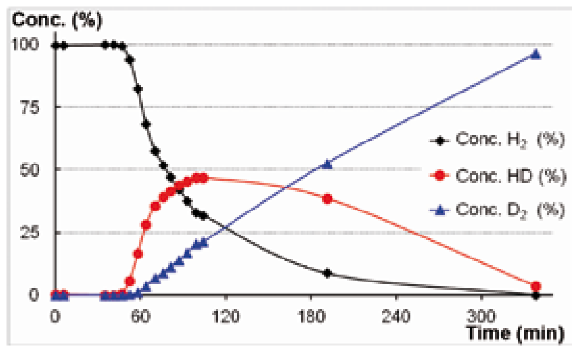


Fig. 7: H_2, HD and D_2 concentrations as a function of time in the bottom product of the CD column while feeding at 0.25 m3 h–1 STP with a 1:1 H_2:D_2 mixture and withdrawing Q_2 at 0.25 m3 h–1 STP from the top of the column.
After four hours of operstion, the bottpm product is composed of 96% D_2, 4% DH and less than 500 ppm of H_2.

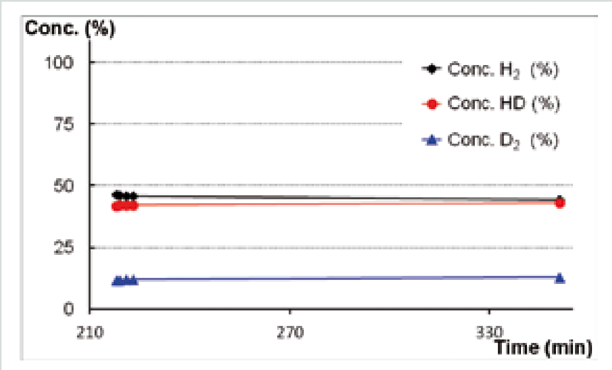


Fig. 8: Head product of the CD column during continuous processing of a starting gas mixture of 50% H_2 and 50% D_2. Over the complete duration, a gas mixture of about 11% D_2, 43% HD, and 56% H_2 is produced in the head of the facility.

taken from the swamp and the head of the CD column allowed for the quantification of the process over the duration of the commissioning tests. Figure 7 presents the hydrogen isotopologues concentration of the swamp product of the CD column analysed by mass spectrometry over a period of about 340 minutes. Figure 8 shows a relatively constant gas composition at the head of the CD column during the same period. In addition, gas samples were taken along the LPCE column and analysed by mass spectrometry and, after oxidation to water, by liquid scintillation (LSC). A decontamination factor of ~10^5 was obtained. Less than 1% of HD remained in the head product of the LPCE column. In this way, functioning of the combined WDS and CD facility was demonstrated.

The research at TRENTA 4 is accompanied by the development of new methods for the analysis of tritium in water and in the liquid hydrogen phase. For the analysis of tritiated water, two processes are studied. The corresponding components are developed and investigated. One method is based on scintillation measurements by using a polymer scintillator. The scintillation light generated by beta radiation in the plastic scintillator is detected with the help of a photo multiplier tube (PMT). Figure 9 shows a PMT modified for the use in tritiated water and the respective measuring cell with a plastic scintillator.

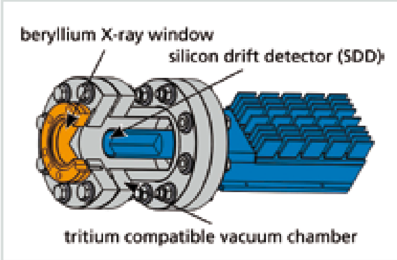


Fig. 10: Tritium-compatible set-up of a BIXS detector with SDD for HTO measurement.

The second method for integrated tritium measurement in water is the so-called BIXS (beta-induced X-ray spectrometry) method. The bremsstrahlung generated by beta radiation in water is measured and evaluated by means of a semiconductor detector (SDD – silicon drift detector). Later, these methods will be integrated in the WDS part of TRENTA and replace manual sampling and measurement. Figure 10 shows a BIXS measuring cell with a SDD for the measurement of tritium in liquid HTO.

To determine the concentration of hydrogen isotopologues in the liquid hydrogen phase at temperatures of about 23 K, hydrogen mixtures are liquefied in a special cell and then analysed by means of IR spectroscopy. Current experiments mainly focus on the characterisation of IR spectra of the individual hydrogen isotopologues (validation of theory), their evaluation for later quantitative measurements, and the identification and development of technical components for IR measurements in the cryogenic temperature range. Figure 11 shows an IR measuring cell for the measurement of liquid hydrogen isotopologues. The liquid level is visible in the window.

These TRENTA can provide for a comprehensive technical and diagnostic solution regarding water detritiation and isotope separation in ITER and future fusion power plants.

Fig. 9: Tritium-compatible PMT and measuring cell (glass right of the column) with plastic scintillator for the measurement of HTO.

Fig. 11: Measuring cell for IR measurements in liquid hydrogen. In the middle of the flange, the liquid level of the 23 K cold hydrogen can be seen.

Preliminary hydrogen plasma experiment for testing a KIT metal foil pump (plasma chamber of CRPP Lausanne).

Results from the Research Areas

Vacuum Technology

Head: Dr. Christian Day

ITEP research and development activities in the vacuum Section keep being focused on vacuum systems for nuclear fusion. On one hand, the vacuum physicists and engineers are involved in the European contributions to ITER, with the highlight in 2012 being the completion of the detailed design of cryopumps for the ITER neutral beam injectors (NBI). These activities are coordinated by the European fusion agency Fusion for Energy (F4E). On the other hand, activities for the European DEMO programme are aimed at preparing a high-performance fusion reactor and have been extended considerably. The researchers did not only prepare an entirely new, liquid metal-based vacuum pump concept, they also extended work to cover the complete fuel cycle. The objective is to develop together with TLK comprehensive software for process simulation and the description of the fuel cycle sub-systems within the next years. This work was performed under the EFDA EURATOM programme.

Cryopumps for ITER

Europe has agreed to supply all primary cryopumps for ITER. In principle, two designs are distinguished, namely, cylindrical pumps for the ITER plasma chamber and very large rectangular pumps for the vacuum vessels of the ITER neutral beam injectors. Both types of pumps are based on the same physical concept, cryosorption on activated charcoal.

To minimise the risks for ITER, both pump types are tested on the 1 : 1 prototype scale. In 2012, F4E invited tenders for the manufacture of the prototype torus cryopump and successfully awarded the contract. One work package, namely coating of the cryopanels that are the main components of every cryopump, will be executed by the Vacuum Technology Section. By mid-2014, the pump will be installed in the institute's TIMO test facility. Similar to the torus cryopumps, the NBI cryopumps are also planned to be tested on the original scale. This test will be performed in the specially constructed MITICA NBI test bed in Padova/Italy. The adaptations of the ITER cryopump design required for this purpose will also be made by the Vacuum Technology Section.

Charcoal coating

The cryopanels of the torus and NBI cryopumps - initially of the prototypes, then of the series pumps - will be coated with activated charcoal using a technology developed by the Vacuum Technology Group. For this large work package (about 1000 cryosurfaces), a new coating facility was constructed. It will start contractual operation in 2013 (see Fig. 1). It is a semi-automatic facility with manual charging and automatic coating and ensures reproducible coating quality.

Expert tasks for ITER

The design phase for ITER components with a very long delivery time has already been completed. Vacuum pumps are among the components that will have to be ready for operation for the first plasma already. To prepare for later operation of the pumps, a simulator was developed for the ITER torus cryopump, by means of which vacuum performance characteristics of the pump can be predicted as a function of operation data (gas flows, valve position, gas type, etc.) (see Fig. 2). The simulation programme combines the methods of direct simulation and Test Particle Monte Carlo simulation. Expertise of the Vacuum Technology Group was extended by application of these methods to ´real´ vacuum problems. In addition, models were developed for the behaviour of the pumps during safety events, such as disruptions.

Vacuum systems for DEMO

Within the framework of the European fusion programme under EFDA, a coordinated programme for the systematic development of a design for DEMO was launched in 2012. This demonstration fusion power plant will be the next step after ITER. In this programme,

Fig. 1: View of the coating facility prior to use.

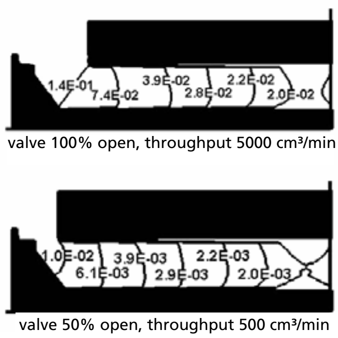


Fig. 2: Calculated pressure (in Pa) of the ITER model cryopump.

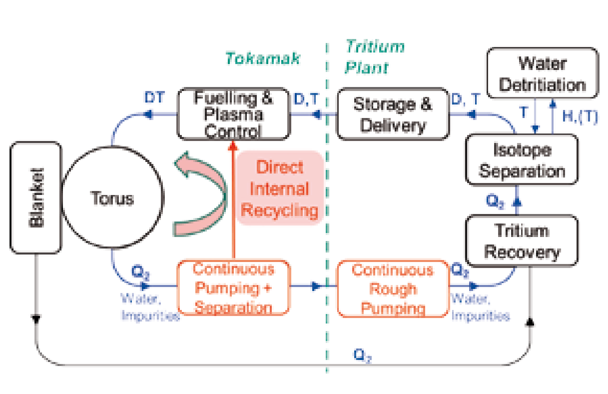


Fig. 3: Schematic representation of the DIR concept for simplification of the fuel cycle.

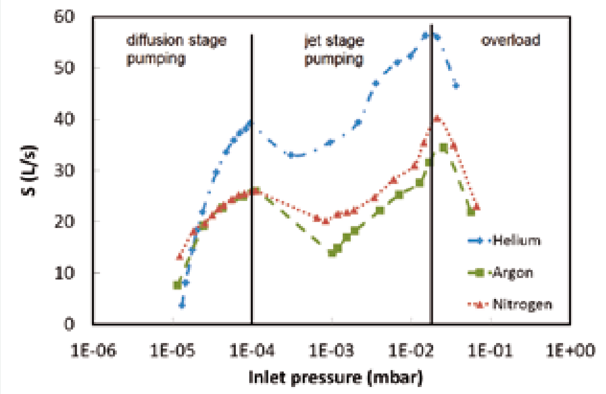


Fig. 5: Pumping characteristics of the mercury diffusion pump for three different gases.

all technical solutions existing for ITER were studied for use in DEMO.

It was found that a mere extrapolation of the ITER fuel cycle to DEMO conditions would not be reasonable. This is mainly due to the intermittent operation of the cryopumps that would result in high tritium inventories and long processing times of the cycled fuel at the long pulse durations of DEMO. Consequently, it is one of the main tasks of the DEMO R&D programme to develop a solution for the divertor vacuum pumps, which shall be operated continuously and do not require any cryogen. Moreover, it would be helpful to extract unburned hydrogen near the divertor and to directly feed it into the reactor via gas injection systems. A first concept was proposed in 2011. In 2012, it was established as DEMO reference concept. This so-called DIR (direct internal recycling) concept (see Fig. 3) consists of three pumping stages.

Fig. 4: Tested mercury diffusion pump.

For separation, metal foils are used. They are permeable for atomic hydrogen only and, thus, provide for a certain compression. For high vacuum pumping, a diffusion pump will be applied. It will be operated with liquid metals to make it tritium-compatible. A liquid ring pump which might be operated with the same liquid metal will be used as a mechanical pump for compression to ambient pressure.

THESEUS test facility

For the validation of this concept, all three types of pumps have to be studied experimentally. In 2012, the THESEUS test facility was constructed for this purpose. It mainly consists of a vacuum vessel with a standardized dosage dome to which the diffusion pump or ring pump can be connected. The facility is designed for operation with hydrogen or deuterium as well as with mercury as a typical liquid metal. To provide for a highly flexible test environment, the facility is equipped with a number of devices, such as a complex gas dosage unit and a fully automatic control and data acquisition unit accommodated in a separate cabinet.

In 2012, an already existing mercury diffusion pump was characterised in the DEMO-relevant operation range (see Fig. 4). This range is characterised by a very high gas load. Consequently, the conventional diffusion pump has to be equipped with a so-called jet stage for further compression. It is obvious from the results (see Fig. 5) that this is possible in principle. In a next step, a simulation tool will be developed for a first conceptual design

Fig. 6: Ring pump rotor.

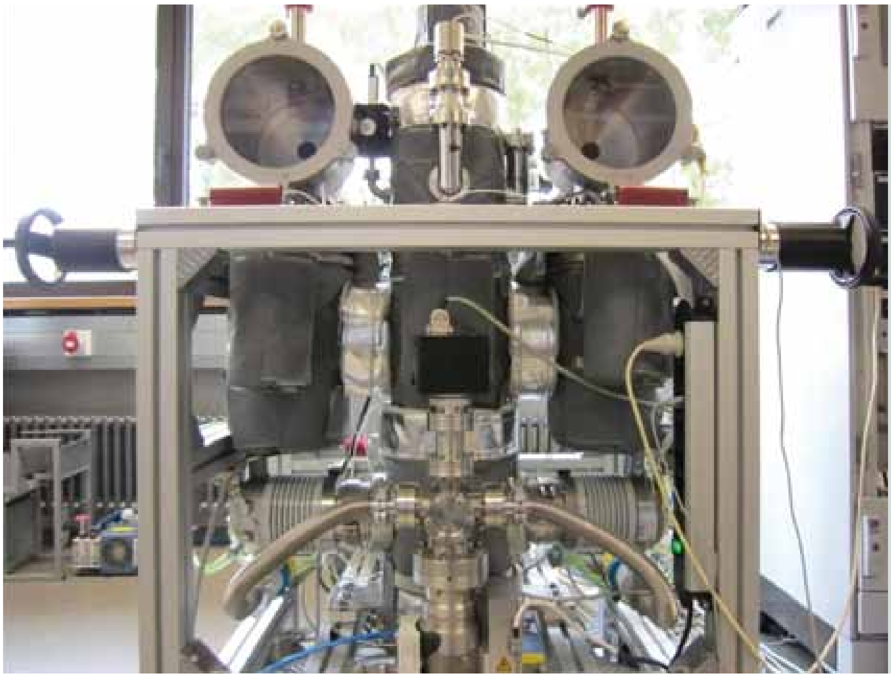


Fig. 7:
OMA test facility.

of a DEMO pump. The computer resources required for this purpose are supplied by the HELIOS supercomputer in Japan.

In 2012, the ring pump was developed and built in cooperation with an industrial company. Figure 6 shows the rotor of the pump during the factory acceptance test using water. The amount of mercury required for filling the pump has already been purchased. Work in 2013 will focus on studying the pump in the mercury operation mode.

For the production of atomic hydrogen, two types of metal foil pumps were compared, namely, ionisation on a hot filament and atomisation in a plasma. First preparation tests were performed in a plasma chamber together with the CRPP Plasma Institute, Lausanne, Switzerland. Work will be continued in 2013.

Outgassing measurements

Outgassing of materials under vacuum conditions is information needed to correctly design vacuum systems. However, the physics of gas outgassing is not yet adequately understood. In practice, vacuum users often apply empirical procedures to correlate the outgassing rate with a certain type of treatment of the outgassing surface. In 2012, the Vacuum Technology Group installed the new OMA facility for measuring outgassing rates (see Fig. 7) and started operation. The OMA facility allows for the experimental resolution of smallest outgassing rates. First measurement results for plastics are highly promising. This work is part of the European Metrology Programme (EMRP).

Networks and cooperation

The KIT-coordinated VACU-TEC European network for the development of vacuum technologies for nuclear fusion has developed well. The five trainees trainees are doing a very successful job.

Under the EFDA activities on "Vacuum technology of DEMO" coordinated by the Vacuum Technology Section of ITEP, successful cooperation started with CCFE, UK, in the field of alternative cryopumps. Experiments in the TIMO-2 cryopump test facility are planned in 2013. In addition, the cryopump systems of the European-Japanese fusion experiment JT60-SA will be assessed using the simulation tools developed within the Vacuum Technology Section for vacuum flows in a large range of Knudsen numbers.

The OMA facility has been included in a programme for the comparison of various concepts. In this connection, cooperation with PTB, Berlin, and the IMT research institute at Ljubljana/Slovenia will be extended.

Highlight: Completion of the NBI cryopump design

The most important milestone reached by the Vacuum Technology Section of ITEP in 2012 certainly was the completion of the design of the cryo pump for neutral beam injection (NBI) for ITER (see Fig. 8).

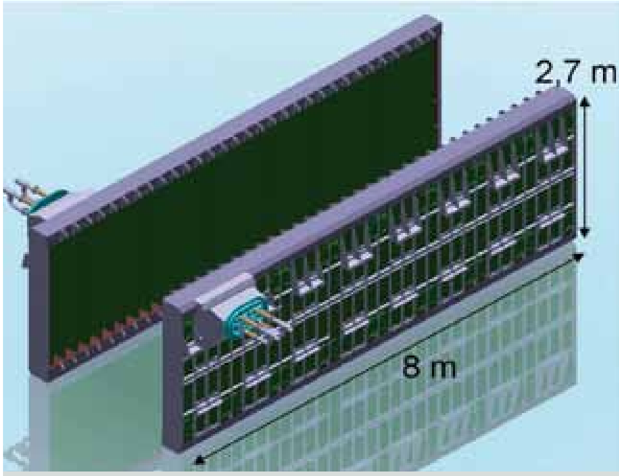


Fig. 8: NBI cryopump. The system consists of two mirror-inverted halves.

Development of the design started in 2004 already and has advanced constantly since then. Based on the built-to-print design, the invitation to tender can be prepared now and manufacture of the pump will start soon. During the development phase, special scientific, technical, and administrative challenges had to be mastered.

Neutral beam injection for ITER is one of three different heating systems, but supplies most of the power. Presently, it is envisaged to install two identical systems with a heating power injected into the plasma of 16 MW each. Use of a third unit is considered as an option. NBI is based on the principle of generating negatively charged hydrogen or deuterium ions, accelerating them in an electric field, re-neutralizing, and injecting them into the plasma. In this way, the plasma is heated up by transferring kinetic energy from the injected beam to the plasma in the reactor. In general, these physical processes are possible only in an environment with an extremely low residual pressure. As the sequential processes in the injector are accomplished by several components, the vacuum system has to meet a special requirement: Instead of selective pumping at a connection flange, a vacuum system is required to generate a specific pressure profile along the beam of the injector (see Fig. 9). This is even more difficult, as several gas sources of variable intensity have to be compensated in the injector. First studies resulted in a translation of the real physical environment and parameters into a model of the ProVac3D Monte Carlo code developed by the Vacuum Technology Group. With the help of simulations, the vacuum experts determined the high requirements to be met by the pump to be developed.

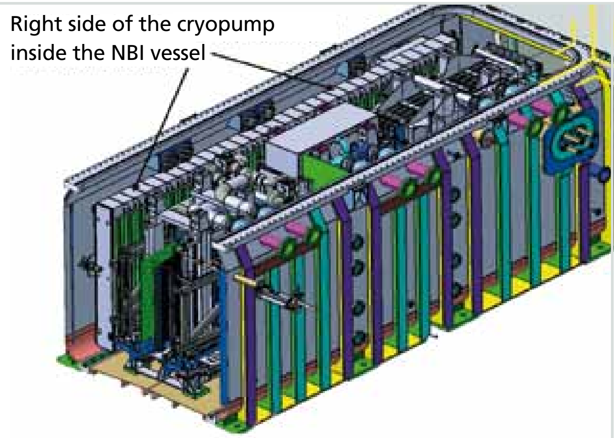


Fig. 9: Cryopump in the NBI vessel. Between the pump halves, the beam guiding components are located for the generation of the neutral particle beam.

Based on the requirement of the so-called capture probability, the three-stage concept of a cryopump was developed. Only a cryopump can reach the extremely high pumping speed required and be operated in the magnetic fields of ITER. The pumping speed reached by the design to be developed amounts to ~ 4700 m^3/s, which is nearly two orders of magnitude above the capacities reached by the largest cryopumps that are commercially available. When developing the three-stage set-up, also the heat loads to be managed were considered. The pump with its adsorbing, i.e. pumping, cryopanels at about 5 K and the thermal shields at about 80 K is operated in a thermally highly active environment. Hence, physicists and development engineers paid considerable attention to the heat loads to be removed by cryogenic panel and shield loops during conceptual design already. The main features of pumping speed and heat loads compete with each other: high-speed pump should be open for the gas, while a closed pump has to accept lower heat loads.

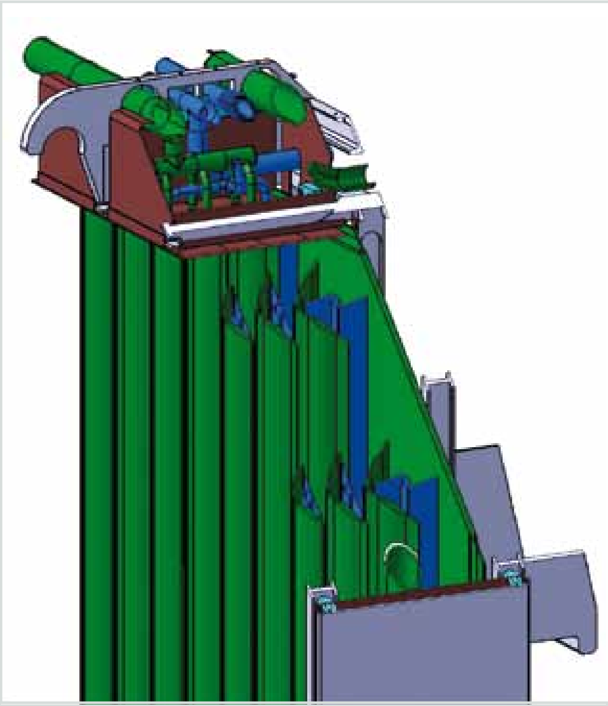


Fig. 10: Partial section of a module. Every half of the pump consists of eight modules of 1 m width. Blue components belong to the cryoloop, green to the thermal shield. Other passively cooled shields of copper are coloured red. Suspension structures are coloured grey.

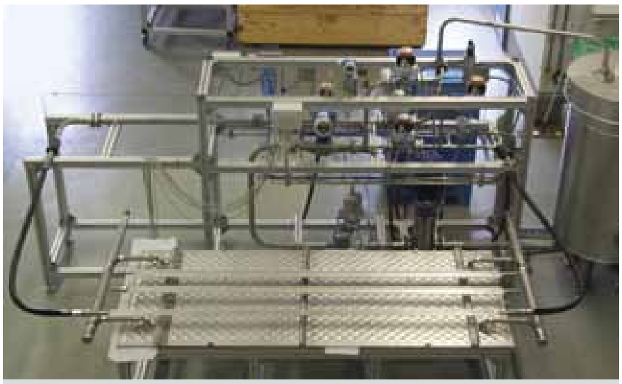


Fig. 11: THEA facility for the experimental determination of pressure losses on shield components.

Upon completion of concept development, detailed design started and took several years until it finally reached the level of manufacture. Connections of all cryopanels and shields were implemented, which represented an extraordinary challenge in view of the space available, complexity, and limited assembly accessability (see Fig. 10). In addition, aspects like homogeneous supply with cryogen, minimum pressure losses, and management of thermally induced length changes and movements had to be considered. At operation temperatures ranging between 4 K and 470 K, enormous thermal movements result due to the dimensions of the pump. For safety reasons, these movements should be compensated largely without bellows. This was achieved by a special suspension of panels and shields.

Another critical aspect was the pressure loss to be expected in the supply of the shield system. As this value cannot be calculated due to the hydroformed, complex inner structure of the shields, the THEA test facility was set up (see Fig. 11). Here, 1 : 1 components were subjected to measurements. On this basis, predictions were made for the complete pump.

Parallel to design work, the pump, all assemblies, and their components were subjected to continuous mechanical and thermal analyses, as shown by the example in Fig. 12. Particular attention was paid to strength, deformations to be expected, and the thermal behaviour in all states of operation. Moreover, detailed analyses of accidents were required. In particular, the behaviour during a seismic event, air ingress or leaks of the NBI system was analysed. Due to the complexity and size of the pump, these analyses were associated with a very high expenditure.

As the design had to be developed to maturity, various aspects had to be considered in detail. For instance, all welds required were specified. All shield components and additional parts were produced as prototypes. Some welds between different materials were tested and optimized in reality (cf. Fig. 13).

The final design includes more than 500 fabrication drawings with about 20,000 individual parts, about 6000 m of weld seams, and about 10 t mass. Hence, it is a highly complex milestone on the way towards implementation in the near future. In addition, administrative obstacles had to be overcome. They resulted from the multi-point organisation of NBI activities under the ITER project and specifications that were modified repeatedly over the contract duration.

In spite of all difficulties, it was succeeded in developing a pump design meeting all requirements, reaching the maximum performance for NBI in ITER, and being the best possible compromise of manufacture and costs. This success is the result of the fruitful cooperation of practicioners and theoreticians, engineers, physicists, and technicians in the vacuum technology field. It is the result of team work, and this is what we are very proud of.

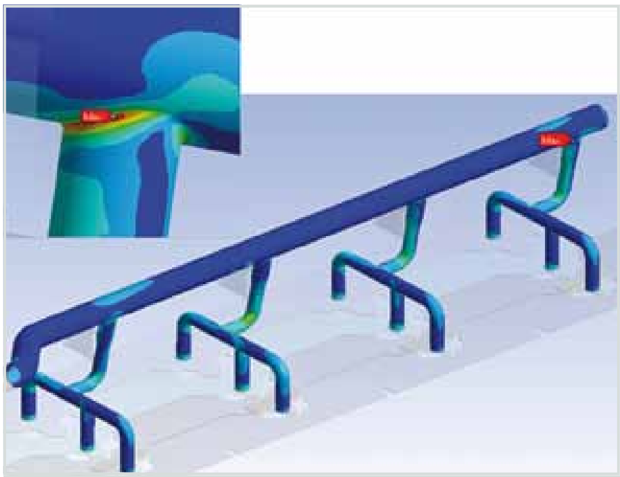


Fig. 12: Detail of thermomechanical analysis. Stresses in the cryodistributor caused by thermal shrinkage.

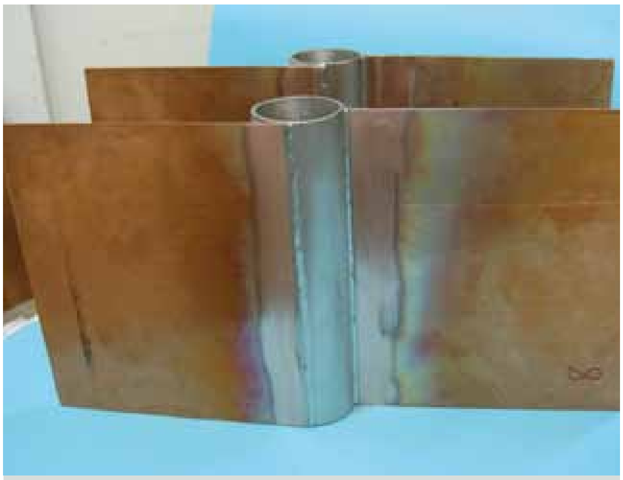


Fig. 13: Manufacturing sample and welding optimisation for a shield component made of a combination of stainless steel and copper.

Helium exhaust gas panel.

Results from the Research Areas

Cryogenics

Head: Dr. Holger Neumann

Croygenics for fusion

In 2012, work of the Cryogenics Division of ITEP under the "Fusion" programme concentrated on two projects: testing of the current leads for the Wendelstein 7X (W-7X) fusion experiment in Greifswald as well as set-up of the CuLTKa (Current Lead Test Facility Karlsruhe) test facility and adaptation of the system to the high-temperature superconductor current leads (HTS-SZF) test for the JT-60SA tokamak in Japan.

Test of W7-X serial current leads in TOSKA

After the successful test of three current lead pairs in 2011, another three tests of current leads were completed successfully in 2012. In total, two prototypes and twelve serial current leads passed the acceptance tests in the TOSKA facility. The last two of the 14 current leads have already been installed in the test facility and will be tested in early 2013 (see Fig. 1).

Set-up of the CuLTKa facility

All cryostats required for the test facility (see Fig. 2) were manufactured by KIT's Technology House and delivered to ITEP. All vessels passed the final leak tests and were installed. All control cabinets were delivered and installed. Meanwhile, field cabling work has started. In 2012, three transfer lines for CuLTKa were specified, tenders were invited, and the orders were submitted to industry. Acceptance at the manufacturer's took place in January 2013.

Upon the delivery and successful acceptance of the first LN2 cooling shield (see Fig. 3) in 2011, delivery of the remaining two cooling shields was delayed by six months. These cooling shields did not pass the final acceptance tests due to major quality deficiencies. The most serious deficiencies were leaks of individual cryopanels and imperfect weld seams. Moreover, insufficient neutralisation of the shields after electropolishing could not be excluded. Consequently, the cooling shields had

Fig. 1: Installation of current leads 13 and 14.

Fig. 3: LN_2 cooling shield with multi-layer insulation.

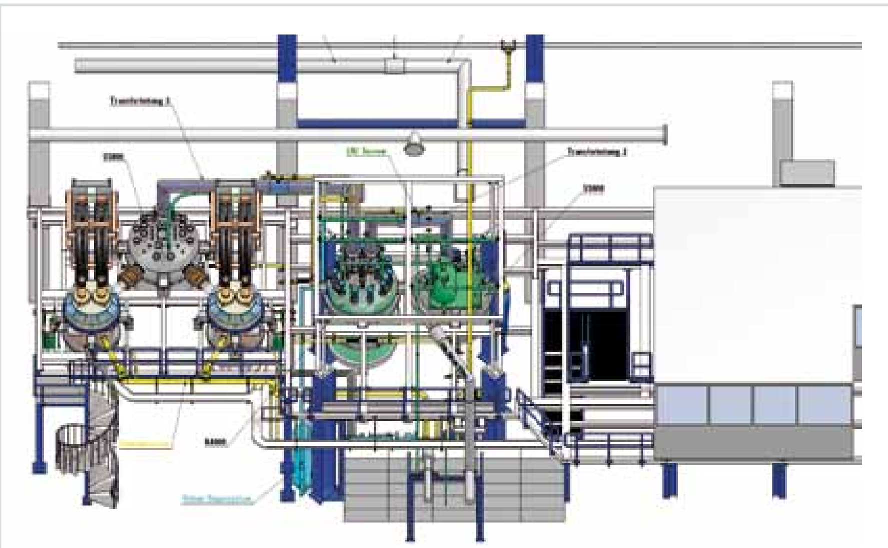


Fig. 2: Layout of CuLTKa.

to be overhauled extensively. Sometimes, even new fabrication was required. Industry will deliver a complete cooling shield as a spare part to minimise outage times in case of leaks of the shields during the current lead tests (see Fig. 4).

Cryogenic infrastructure

Work relating to the cryogenic infrastructure in 2012 included extensive maintenance, repair, and service activities. Existing low-temperature experimental facilities were extended, adapted, and operated.

In addition, new installations were designed and commissioned for various research projects.

Activities included among others:

- Extensive modification of the ventilation system in the sound hood of the compressor of the 2 kW cryogenic facility.
- Total revision of screw compressors V2 and V3 of the 2 kW cryogenic facility (see Fig. 5).
- Exchange or installation of new valve drives.
- Extension of a hot helium gas line to building 411.
- Reconstruction or renewal of the filling station for helium pressure gas vessels.
- Modernisation of the cooling loop of the 300 W refrigerator.
- Purchase of an evaporator for the LN_2 tank in building 456.
- Installation and reconstruction of components of the 500 W refrigerator (see Fig. 6).

The 300 W (1.8 K) He refrigerator was operated for about 1318 hours in 2012. Of these, 536 hours were spent for liquefaction operation, 97 hours for purging as well as for cool-down and warm-up of the system, which leaves 685 hours of pure refrigeration time for experiments in the high-field magnet laboratory.

In 2012, the 2 kW (4.5 K) He refrigerator was run for approximately 1747 hours, with 199 hours liquefaction operation, 141 hours purging operation as well as cool-down and warm-up. Hence, 1404 hours were spent for refrigeration for fusion experiments.

In total, the facilities liquefied about 193,226 litres of helium. 134,648 litres were used for experiments at ITEP, 58,578 litres by other institutes.

Fig. 5: Disassembly of the He screw compressor V3 of the 2 kW He refrigerator for revision.

The 500 W (4.5 K) He refrigerator for the KATRIN experiment was operated for 200 hours only in 2012. Of these, about 19 hours were spent on purging, cool-down, and warm-up of the facilities. Operation was required for test measurements of WGTS tube cooling. No failures worth mentioning occurred. Maintenance work was performed as planned. Institutes without any return gas line to ITEP were informed about the status of helium resources. ITEP succeeded in convincing the ANKA-ISS institute of the benefits associated with the construction of a return gas line.

Cryogenics for REUN

Under the "Efficient Energy Conversion and Use" (REUN) programme, the Cryogenics Division was involved in the projects of LIQHYSMES, Basics for the HTS Generator, and SUPRAPOWER.

Fig. 4: Cycling of the cooling shield with LN_2 + leak test.

Fig. 6: Heating control and insulation of the activated charcoal adsorber of the 500 W refrigerator.

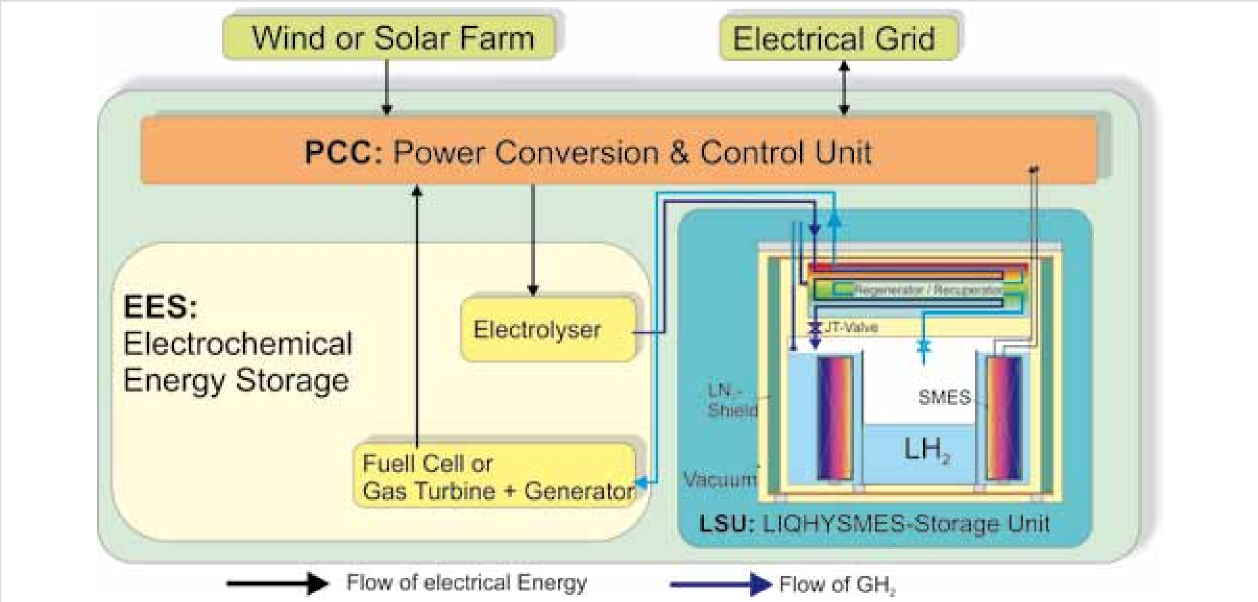


Fig. 7: LIQHYSMES, an electrochemical conversion unit, and a converter and control unit connected to regenerative energy producers and the consumer grid.

LIQHYSMES

Further studies were performed with regard to a hybrid energy storage system based on liquid hydrogen and a superconducting magnetic energy storage system, called LIQHYSMES (LIQuid HYdrogen & SMES). The principle set-up is shown in Fig. 7. Via a converter and control unit, alternative energies are fed into the grid. The unit can also take up excessive energy from the grid. Excessive energy is stored in the form of LH_2 in the LSU unit by electrolysis or in the form of magnetic energy in the SMES.

To compensate short-term fluctuations, the SMES can release energy again in the sub-second range. To buffer long-term deficits in energy production, the liquid hydrogen can be fed back into the grid as electricity via fuel cells or alternatively via gas turbines and a downstream generator.

Since September 2012, the project of three years' duration has been funded under the EWI hydrogen initiative.

Basics for an HTS generator

The BMWi-funded cooperation project "Basics for an HTS Generator" of Siemens and KIT started in February 2011. It is aimed at creating major prerequisites for the use of high-temperature superconductor technology in electric generators. For this purpose, a rotating test rig with an HTS coil is planned to be set up. The coil is to be cooled to 30 K by a neon-driven thermosyphon.

The original plan to construct a metal spin bunker for slip control was given up for reasons of costs. Instead, it is now planned to construct a spin bunker of sand, as shown in Fig. 8. To calculate the required wall thickness, a study is presently being accomplished by the Universität der Bundeswehr, Munich.

SUPRAPOWER

The SUPRAPOWER (SUPerconducting, Reliable, lightweight, And more POWERful offshore wind turbine) EU project started on December 01, 2012. The project is aimed at developing a superconducting generator for offshore wind turbines. Under this project, KIT develops a rotating cryostat for the superconducting MgB_2 coils. Gifford-McMahon coolers made by Oerlikon Leybold Vacuum are available for cooling. Cooling is to be based on pure thermal conduction.

Safety in cryogenics

Manfred Süßer and Professor Steffen Grohmann participated in the DIN standards committee NA 016-00-07AA for the protection of pressure vessels in cryogenics. Moreover, Carolin Heidt wrote a diploma thesis on the modelling of pressure increase in a liquid helium tank in the event of a collapse of the insulating vacuum. Within the framework of a PhD project, the findings will be verified experimentally and further developed. Mrs. Frank studied the bleeding behaviour of safety valves for her bachelor thesis.

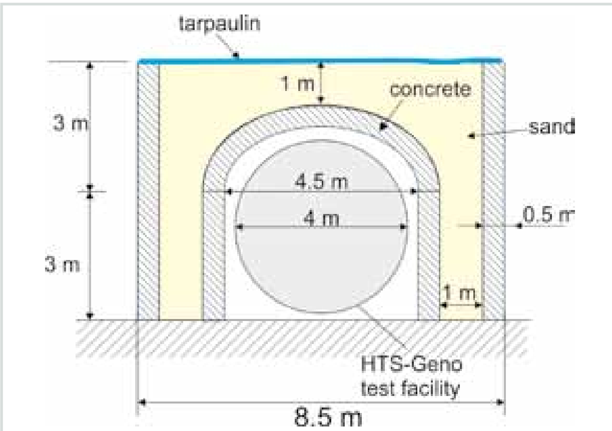


Fig. 8: Sand spin bunker for a test rig to study HTS components for superconducting generators.

October 2012: Removal of the KATRIN demonstrator. Within the next two years, it will be turned into the final WGTS.

Results from the Research Areas

KATRIN, Karlsruhe Tritium Neutrino Experiment

Head: Dr. Beate Bornschein

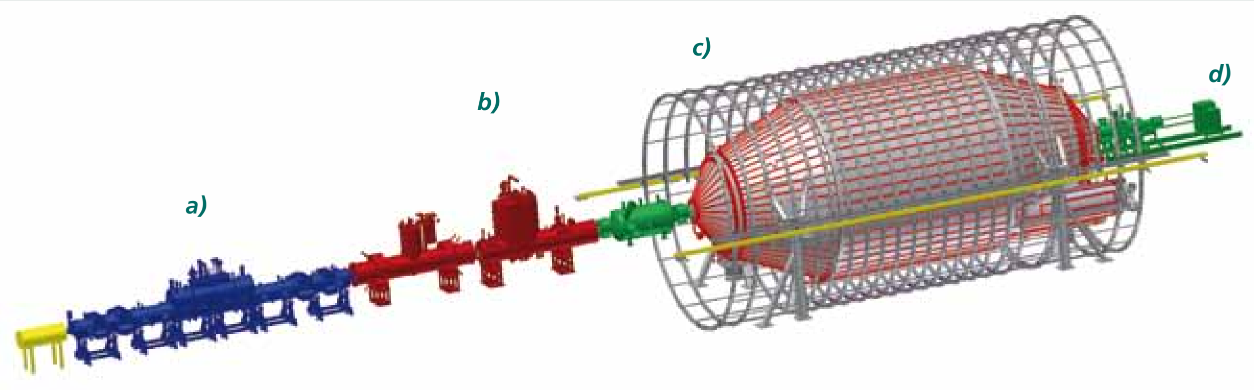


Fig. 1: Schematic representation of the KATRIN international large-scale experiment. The electrons produced by β-decays in a high-intensity windowless molecular tritium source (WGTS, [a]) are passed through a tritium pumping station with the active and passive elements DPS2-F and CPS (b) to a system (c) consisting of two electrostatic spectrometers (roughing and main spectrometers). All electrons that passed the spectrometers are counted by a semiconductor detector (d).

KATRIN, the Karlsruhe Tritium Neutrino Experiment, is targeted at measuring the neutrino mass with a sensitivity of 200 meV/c^2 in a model-independent manner. The motivation of KATRIN is the key role played by neutrinos in astroparticle physics: On the one hand, mass-carrying neutrinos as hot dark matter are involved in the evolution of large scale structures in the universe. On the other hand, the neutrino mass itself is the key to solving the problem of the origin of mass.

The experimental principle of KATRIN is based on the precise measurement of the spectrum of electrons produced by the β-decay of molecular tritium near the kinematic end-point of 18.6 keV. For this purpose, electrons from a windowless gaseous tritium source of luminosity are led adiabatically through the 70 m long experimental facility by high magnetic fields of superconducting magnets. A system of two electrostatic retarding spectrometers the electron energies determine with a resolution of 0.93 eV (see Fig. 1).

A worldwide collaboration of more than 150 scientists, engineers, and technicians under the coardination of KIT is currently in the process of building this key experiment in astroparticle physics in the Karlsruhe Tritium Laboratory (TLK). First data are expected to be obtained in 2014. The design, construction, and successful execution of the KATRIN experiment impose very strict requirements on process technology, especially tritium process technology, ultrahigh vacuum technology and cryotechnology as well as on high-voltage stabilisation technology. In addition, an adequate project management is required to allocate manpower and funding to the objectives of KATRIN in terms of time and tash.

Within the framework of the KATRIN experiment, the ITEP is responsible for tritium process technology as well as for cryotechnology. Several leaders of partial projects (task leaders) in this area come from ITEP. More than 95% of ITEP's scope of work concentrate on the so-called source and transport system shown in the diagram in Fig. 2. As tritium is used, the system is set up completely within the TLK.

The main component is a superconducting magnet system of 16 m length, called WGTS. It contains the gaseous tritium source in a cold beam tube at 30 K. The so-called calibration and monitoring system (CMS) is located in the rear part on the beam tube, the transport system is installed in the front part (towards the spectrometer). Via the transport system, the tritium decay electrons are guided to the spectrometer. At the same time, the tritium gas flow into the spectrometer system is reduced by more than twelve orders of magnitude with the help of pumps. For this purpose, a differential pumping section (DPS2-F) and a cryopumping section (CPS) at 3.5 to 4 K are operated. DPS2-F and CPS house superconducting magnet systems with a length of 7 and 9 m, respectively. Like the WGTS, they are (CPS) or were (DPS2-F) manufactured by external companies under ITEP's supervision.

The tritium loops (inner loop, outer loop) for controlled tritium gas supply and a tritium purity above 95% are also shown in Fig. 2. Simultaneous stable supply and removal of tritium gas by pumps results in a stable gas column density in the beam tube of the WGTS (tritium source).

The status of activities will be outlined in the following paragraphs.

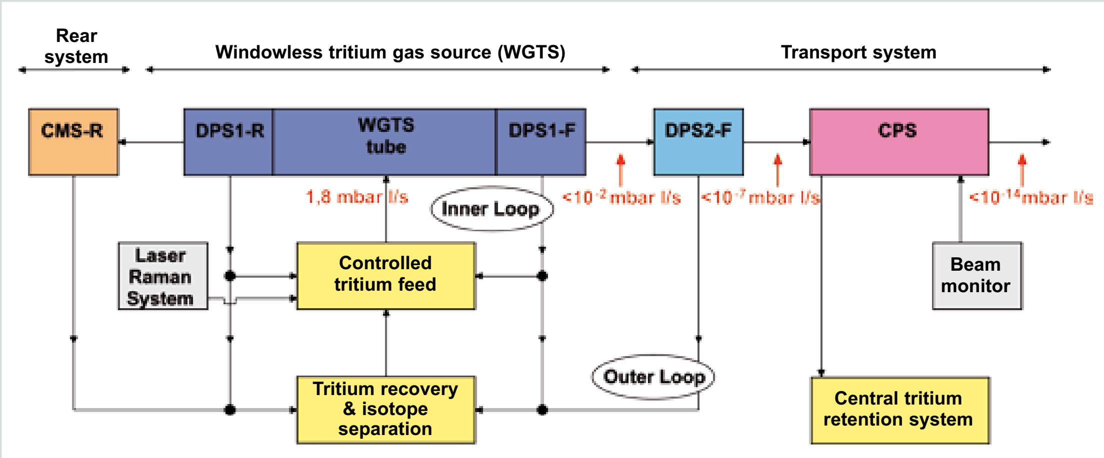


Fig. 2: Scheme of the KATRIN tritium source and its interfaces to the TLK infrastructure.

WGTS and demonstrator

After the mutual termination of the contract with the VARIAN company in autumn 2011, KIT alone has been responsible for the further construction of the WGTS. Major work packages that remain to be executed are the fabrication of the differential pumping sections and the modification of the demonstrator tested at TLK to the central component of the WGTS. The demonstrator actually is a shortened version of the WGTS without superconducting magnets. It was constructed only for testing the new and highly complex cooling concept for the 30 K tritium source. Upon the successful test of the WGTS magnet modules at Saclay, where the quench concept was checked as well, the WGTS can be set up. The construction work required will be executed at KIT. The same applies to the development of the magnet control system. For fabrication, KIT contracted the company research instrumentation. The WGTS will presumably be assembled at TLK by 2014.

DPS2-F

After successful commissioning of the DPS2-F, the scientific programme had to be stopped in 2011 due to a quench of a DPS2-F magnetic field coil. During this quench, one of the diodes protecting the coil against overvoltage was destroyed. Without this diode, another quench might lead to the destruction of the magnet system. Analysis of repair options took several months and revealed the necessity of an exchange of all protection diodes used by another type and of accessibility of the diodes from outside. After detailed analysis and discussion with ASG, it became clear that a modular new construction of the system, i.e. purchase of five individual standard systems and manufacture of the beam tube in own responsibility (see Figs. 3 and 4) is cheaper and quicker than to repair the old system. After setting up the specification, tenders for the five magnet modules were placed in late summer 2012. In November 2012, a fabrication contract was concluded with the company "Cryomagnetics". The magnet modules are planned to be delivered in late 2013. In the meantime, the beam tube that has to be constructed according to specifications of TLK will be completed.

Fig. 3: New concept for the differential pumping section of KATRIN. Shown are the five superconducting magnets and two of the five planed pumping chambers.

CPS

The CPS is being built by ASG, Genoa. Fabrication is accompanied by an inter-institute project team of KATRIN. In 2012, quality assurance work focused on the supervision of the repair of the beam tube that had been damaged during assembly and on the control of the individual fabrication steps. For this purpose, KIT also contracted external staff. Moreover, the new protection diode concept for the superconducting magnets was approved and a first conceptual design was made for its practical implementation. In parallel, a test rig for the cold test (at 4.2 K) of the protection diodes prior to their final assembly by ASG was constructed at ITEP.

Fig. 4: Sketch of the interface between DPS and WGTS. At this point, an additional pumping chamber is to be installed in order to reach the necessary tritium flow reduction factor of 10^5 at least.

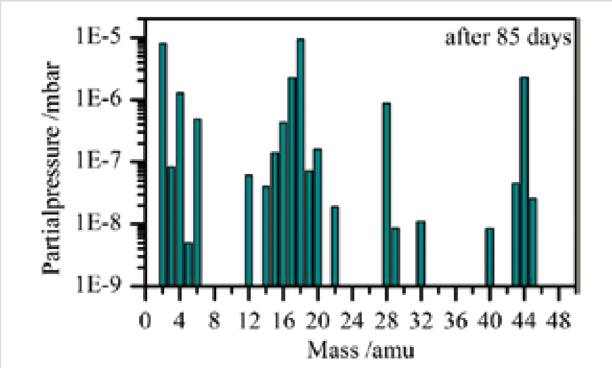


Fig. 5: Results of the fifth measurement series of the TriToP experiment. The mass spectrum was recorded after 85 days of continuous operation with tritium (flow rate 20 sccm) by means of a residual gas analyser.

According to the current schedule, the CPS is to be delivered to KIT by late 2013. By that time, the seven control cabinets will have been delivered as well. They are required for the cryogenic operation of the CPS, i.e. for the control of the more than 420 sensors and valves. ITEP developed the system concept. It is manufactured by an external industry partner.

Cryofacility and cryotransfer line

Work in 2012 concentrated on the fabrication of the third part of the cryotransfer line and the third valve box required for cryogenic connection of the CPS. Meanwhile, fabrication is nearly completed. Delivery and assembly are planned to take place in 2013. Another focus was placed on the cryotechnical support of the KATRIN detector system that started operation in 2012. The detector system includes two superconducting magnets made by the company "Cryomagnetics" and a nitrogen-cooled semiconductor pixel detector.

Tritium loops

The tritium loops of KATRIN are developed and built at the TLK, among others within the framework of bachelor, diploma, and PhD theses. In 2012, work focused on the set-up of new experiments and on the continuation of measurements in the TriToP and TriReX tritium experiments.

In TriToP (Tritium Test of Pump), a turbomolecular pump (TMP) with magnetic bearings of the type MAG2800 is being tested in long-term operation with tritium. Operation conditions correspond to those of the eight turbomolecular pumps of the first two pumping chambers of the WGTS. After test operation for one year, it was found that continuous operation of the MAG2800-type TMP under KATRIN conditions is possible. Over the said period, the pump survived a flow rate of more than 1 kg tritium. Apart from this excellent result, however, a shortcoming was observed: Figure 5 shows a mass spectrum recorded after 85 days of permanent operation. The pump exhibited ageing phenomena after a downtime of several weeks with increased tritium partial pressure. The researchers attribute these phenomena to the degradation of O-rings and epoxy resin. In late November 2012, the respective pump was disassembled in a special glove box at TLK in the presence of a specialist from Leybold in order to examine the interior in more detail.

TriReX (Tritium Rear System Experiment) serves to study the possibility of determining tritium concentration in the WGTS by means of Bremsstrahlung (BIXS method). Bremsstrahlung is generated in the rear wall of the WGTS by the tritium decay electrons. TriReX imitates the rear wall of KATRIN by a small gold-coated beryllium wall. After first basic tests in 2011, the experimental set-up was optimized in 2012. First measurements with the optimized system were highly successful. The team presented the results at SOFT2012.

Based on the R&D results obtained in TriReX, the TRIADE experiment will be set up to measure tritium adsorption on gold and other materials by the BIXS method. It is aimed at reaching a detection limit of 0.1 monolayers. The attempt to determine tritium adsorption on gold with a vibrating quartz (TriQuarz experiment) was given up, because the sensitivity is not sufficient compared to the TRIADE experiment.

R&D activities relating to laser Raman spectroscopy will be described in the "Highlight" section.

Acknowledgement

Work relating to KATRIN was performed successfully by ITEP in an interdisciplinary manner, with TLK having the major share of the tasks. All areas profited from a close and fruitful cooperation with students, technicians, engineers, and scientists of ITEP, the Institute of Nuclear Physics (IKP), the Institute of Experimental Nuclear Physics (IEKP), the Central Workshop (TID-F), and the KIT Project Management Group (PMQ). Thanks to all of them!

Highlight: Raman spectroscopy for inline analysis of tritium gas mixtures

Quantitative analysis of gas flows of hydrogen isotopologues (H_2, HD, D_2, HT, DT, T_2) is indispensible for both the tritium source of the KATRIN experiment and the fuel cycle of a fusion reactor. For this purpose, Raman spectroscopy is applied. In the past years, this method was developed further by researchers of TLK.

Raman spectroscopy is a spectroscopic method based on the inelastic scattering of laser light at the molecules of the sample. Energy is transfered into rotational/vibration excitation of the molecule, as a result of which the scattered light experiences a characteristic red shift of its wavelength. A typical Raman spectrum is shown in Fig. 6.

Accurate calibration of Raman systems

Generally, Raman systems produce spectra, from which line intensity only can be extracted. To derive the composition of the sample, so-called response functions are needed, which are individual for each characteristic line of the Raman spectrum. This relationship is visualised in Fig. 7.

Usually, reference samples of known composition are used for the calibration of analytical systems. When using mixtures containing tritium, however, its radiochemical properties have to be considered. They limit the accuracy of the gas samples, which is mainly due to processes causing reactions of the gas molecules with the stainless steel walls and self-equilibration of the gases. For H/T mixtures, this reaction is given by $T_2 + H_2 \leftrightarrow 2HT$.

Another calibration method is based on the calculation of intensities of the Raman lines. As hydrogen isotopologues (H_2 to T_2) are relatively simple molecules, the so-called polarisability can be calculated by quantum mechanics. From this, line intensities can be derived. However, these calculations have not yet been confirmed experimentally, nor have potential uncertainties of these models been quantified. In addition, the method requires wavelength-dependent, spectral sensitivity that varies for every Raman system.

Both calibration methods were developed and applied by TLK (see Fig. 6). Method 1 yields response functions for all six isotopologues. Quantum mechanical calculations were verified by so-called depolarisation measurements. By means of a novel method, the measurement error due to geometrical effects and polarisation impurities was reduced.

The spectral efficiency was calibrated by using a fluorescence standard ensuring maximum accuracy and optimum imaging of the scattering region (see Fig. 7).

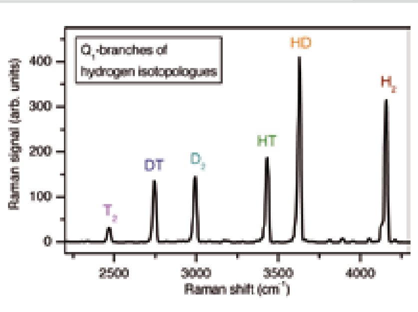


Fig. 6: Raman spectrum of all six hydrogen isotopologues.

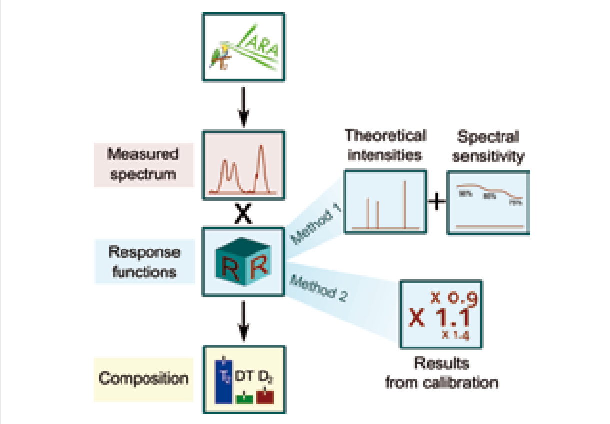


Fig. 7: Calibration of Raman systems by two complementary methods.

For method 2, a mixing system was set up to produce highly accurate gas mixtures of the non-radioactive molecules H_2, HD, and D_2. The response functions of H_2, HD, and D_2 were determined with an uncertainty of < 0.5% and compared with the calculations using method 1. It was found that the results of both methods are in agreement with a deviation of less than 2%. This justifies the use of method 1 for the calibration of all isotopologues.

The accuracy achieved of < 3% exceeds the requirements specified for KATRIN (~ 10%) by far. It was demonstrated that method 1 only will be required for future calibrations of Raman systems and that calibration samples will no longer be needed.

Tritium stability of optical coatings

In a Raman system, the Raman cell (see Fig. 8) is in contact with tritium and, hence, exposed to beta radiation. After the operation of the Raman system at the LOOPINO tritium test loop for three months, the anti-reflective coatings of the Raman cell windows were found to be damaged.

At the high tritium concentration (more than 90% at 200 mbar total pressure), this damage may probably be caused by the intensive beta radiation. In addition, radiochemical processes cannot be excluded. To study the effect of beta radiation on optical coatings in more detail, an experiment was set up, in which coated windows are exposed to tritium gas. Apart from the type of coating used so far, samples of increased radiation resistance are analysed. During the studies, the windows are repeatedly stored in tritium gas for several days.

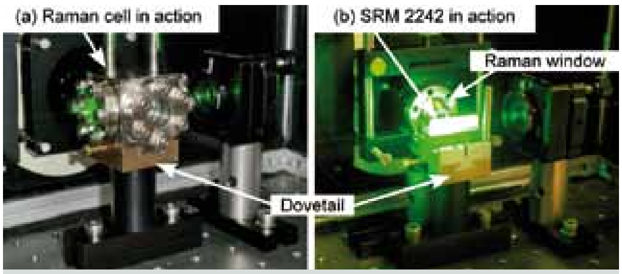


Fig. 8: The fluorescence standard is put at the place of the Raman cell in order to determine spectral efficiency of the Raman system.

Afterwards, optical properties of the windows are characterised. For characterisation, light microscopy methods and a set-up for the measurement of transmission and reflection properties of the windows are applied (see Fig. 9). First measurements revealed first indications of a damage on the coating used for the cell windows so far after 17 days already. By optimising the polarisation-sensitive optical components in the set-up, a long-term stability of 3% was reached over a duration of more than 100 hours. Upon the completion of optimisation and the installation of reference samples for regular calibration of the system, the measurement series will be continued and all coated windows will be exposed to pure tritium for at least 60 days. This period corresponds to the duration of a typical measurement cycle of the KATRIN experiment with continuous operation of the Raman system.

Automatic analysis of Raman spectra

For the KATRIN experiment and for monitoring the gas composition in the fuel cycle of a fusion power plant, automatic and accurate analysis of the Raman spectra is required. The analysis routines developed by the Tritium Laboratory comprise several steps to process the Raman spectra, determine line intensities, and convert them into concentrations with the help of the above-mentioned response functions. The process computer automatically executes all analysis steps directly after the acquisition the Raman spectrum. The complete analysis of a Raman spectrum takes less than 5 s. Hence, it allows for a near-to-realtime monitoring of the gas composition and process control. As data acquisition and data analysis are combined in one programme, even staff not specialised in Raman spectroscopy can performe Raman analyses.

Application of Raman spectroscopy at TLK

Based on the experience gathered from the operation of two Raman systems, the Raman system envisaged for the KATRIN experiment was set up and tested. Measurements revealed that the gas composition can be determined with a precision of 0.1% within a recording period of 60 s. This is far below the maximum allowed recording duration of 250 s.

In the TriToP (Tritium Test of Pumps) experiment, Raman spectroscopy was applied in addition to the already existing mass spectrometer. It is the objective of the experiment to study the stability of a turbomolecular pump repeatedly used in KATRIN under tritium atmosphere. As the mass spectra could not be interpreted clearly due to the isotope effects of H, D, and T and the numerous molecule masses, the Raman spectra yielded additional information on the gas composition.

Apart from monitoring gas composition in the KATRIN experiment, Raman spectroscopy is also suited for process control in other tritium experiments. For this purpose, a mobile glove box was developed. It can be used the optical Raman system to connect any glove box without modifications being required. The mobile glove box is presently being set up (see Fig. 10) and will be commissioned in spring 2013 in the TRENTA facility. This facility is used to develop water detritiation and isotope separation for the ITER fusion reactor. A few per cent of tritium exist in the hydrogen gas of 1 – 5 bar total pressure. As a result of the total pressure that exceeds the pressure of KATRIN by one order of magnitude, recording time of the Raman spectra can be reduced considerably and gas composition can be determined every 5 to 15 s. The tritium analysis methods used so far had to be carried out manually and took up to 15 minutes for one measurement. Hence, Raman spectroscopy considerably improves process control in the TRENTA facility.

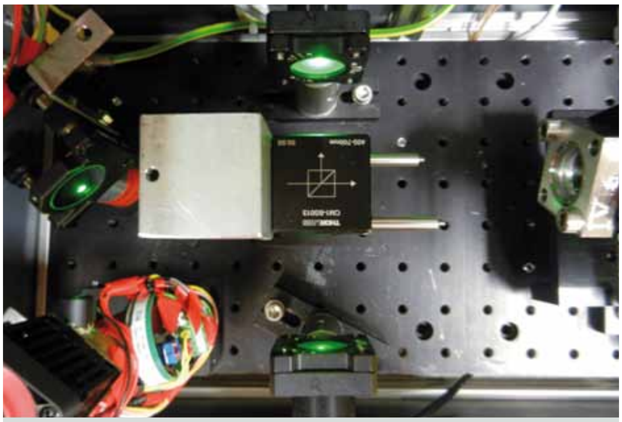


Fig. 9: Set-up to determine the transmission properties of a coated window in a glove box. The sample to be analysed is shown on the right.

Fig. 10: Mobile glove box for connection of the Raman system (right) to any other glove box.

Teaching and Education

Lectures, Seminars, Workshops, Summer Schools

Lectures

KIT-Fakultät Elektrotechnik und Informationstechnik
Supraleitende Systeme für Ingenieure (Noe, Neumann, Siegel) WS 11/12–12/13
Supraleitertechnologie (Noe, Schlachter, Weiss) SS 12
Superconductivity in smart grid power applications (Grilli, Noe) SS 12
Seminar Projektmanagement für Ingenieure (Noe, Day, Grohmann) SS 12

KIT-Fakultät für Chemieingenieurwesen und Verfahrenstechnik
Vakuumtechnik I (Day, Varoutis) WS 11/12–12/13
Kryotechnik (Neumann) WS 11/12–12/13
Kältetechnik I (Grohmann) WS 11/12

KIT-Fakultät Maschinenbau
Fusionstechnologie A* (Bornschein, Day, Fietz, Weiss) WS 11/12–12/13
Vakuumtechnik und Tritiumbrennstoffkreislauf (Bornschein, Day, Demange) SS 12

KIT-Fakultät Physik
Messmethoden und Techniken in der Experimentalphysik (Bornschein) SS 12
Hauptseminar Astroteilchenphysik: Neutrinos und dunkle Materie (Bornschein) WS12/13

Leibniz Universität Hannover – Fakultät Elektrotechnik und Informationstechnik
Neue Komponenten der elektrischen Energieversorgung* (Noe) SS 12

House of Competence
Blockseminar Wissenschaftliches schreiben und präsentieren für Physiker (Bornschein) WS 12/13
Mikromodul Physik* (Bornschein) WS 12/13

Duale Hochschule BW – Fachbereich Maschinenbau
Arbeitssicherheit, Konstruktionslehre I und Umweltschutz (Bauer) SS 12
Thermodynamik 1 für Maschinenbauer (Neumann) WS 11/12–12/13
Thermodynamik 2 für Maschinenbauer (Neumann) SS 12

Seminars / Summer Schools / Workshops

3rd ITEP Young Scientists Seminar
16.–19. Januar 2012, Kristberg, Österreich

3. ZIEHL – Zukunft und Innovation der Hochtemperatur-Supraleitung in der Energietechnik – Workshop*
6.–7. März 2012, Bonn

VDI-Seminar Kryotechnik
14.–16. März 2012, Karlsruhe

IEA Exco Meeting
10.–11. Mai 2012, Heidelberg

CIGRE Working Group Meeting D1.38*
4.–6. Juni 2012, Schenectady, USA

6th ESAS Summer School on Materials and Applications on Superconductivity*
11.–15. Juni 2012, Lens en Vercors, Frankreich

6. Karlsruhe-Dresden Doktorandenseminar zur Supraleitung
20.–22. Juni 2012, Bad Liebenzell

2. Doktorandenseminar Fusion*
20.–21 Juni 2012, Bad Herrenalb

6th International Summer School on Fusion Technologies*
3.–14. September 2012, Karlsruhe

VDI-Seminar Cryogenics
19.–21. September, Karlsruhe

DKV-Tagung 2012*
21.–23. September 2012, Würzburg

Coated Conductor for Application Workshop 2012*
14.–16. November 2012, Heidelberg

School on Vacuum Technology
20.–22. November 2012, Karlsruhe

Die Kunst sich Selbst zu präsentieren
3.–4. Dezember 2012, Karlsruhe

* with participation of ITEP

Teaching and Education

Doctoral Theses – Master- and Diploma Theses – Bachelor Theses

2012 Doctoral Theses (*completed)

Martin Babutzka (TLK)
Entwicklung, Aufbau und Integration des Calibration und Monitoring Systems (CMS) am KATRIN-Experiment

Christian Barth (FUSION)
Mechanisch stabilisierte Hochtemperatur-Supraleiter-Kabel

Olga Borisevich (TLK)
Simulation and experimental study of a multi-stage permeation process for tritium recovery in breeder blanket

Florian Erb (SUPRA)
Entwurf supraleitender Windkraftgeneratoren

Sebastian Fischer (TLK)
Laser Raman Spectroscopy For The KATRIN Experiment

Patthabi Vishnuvardhan Gade (FUSION)
Optimization of High Temperature Superconductor cable concepts for high current capacity to be used in HTS coils for future fusion reactors

Thomas Giegerich (VAKUUM)
Entwicklung eines Vakuumpumpkonzepts für zukünftige Fusionsreaktoren

Cristian Gleason-González (VAKUUM)
Modelling of rarefied neutral gas flow

Robin Größle (TLK)
IR-Spektroskopie an flüssigen Wasserstoffisotopen und Entwicklung einer Methode zur Bestimmung der Tritiumkonzentration im Brennstoffkreislauf von ITER

Zoltan Köllö (TLK)
Further Development of Tritium analytic devices

Philipp Krüger (SUPRA)
AC Loss characterization of HTS devices for power applications

Olaf Mäder* (SUPRA)
Stabilität von Hochtemperatur-Supraleitern

Robert Michling (TLK)
Performances Assessment of Water Detritiation Process

Oliver Näckel (SUPRA)
Untersuchungen strombegrenzender Spulen

Florian Priester (TLK)
Optimierung der KATRIN Tritium-Loops

Enrico Rizzo (FUSION)
Thermal-fluid dynamic and electrical optimization of high temperature superconductor current leads for fusion magnet systems

Marco Röllig (TLK)
Tritiumanalytik bei KATRIN

Magnus Schlösser (TLK)
High-precision Laser Spectroscopy on Hydrogen Isotopologues

Kerstin Schönung (TLK)
Aufbau Rear-System von KATRIN

Sebastian Hellmann (SUPRA)
Technologieentwicklung für supraleitende strombegrenzende Transformatoren

Christoph Bayer (FUSION)
Characterization of high temperature superconductor (HTS) cable for large scale HTS magnet coil application

Mater- and Diploma Theses 2012 (*completed)

Christoph Bayer*
Bestimmung des Pinningverhaltens technischer Hochtemperatursupraleiter

Alexander Beck
Design und Aufbau eines tritiumkompatiblen IR-Spektroskopiesystems zur Untersuchung flüssiger Wasserstoffisotopologe

Miroslav Dimov
Untersuchungen zur Entwicklung eines Prototyp-Sensors für ein neues thermisches Messverfahren zur Durchflussmessung

Amit Grover
Development, construction and test of a flexible support structure for multi-layer insulation in a flexible cryogenic transfer line

Carolin Heidt*
Untersuchungen zur Sicherheit von Flüssighelium-Druckbehältern

Sebastian Hellmann*
Untersuchung der Homogenität des Quenchverhaltens von HTS Multileiterkonzepten in Hinblick auf die Anwendung in supraleitenden Transformatoren

Florian Kassel
Weiterentwicklung der Laser-Ramanspektroskopie an gasförmigen Wasserstoffisotopologen zur Prozessüberwachung von Tritiumexperimenten

Simon Niemes
Inbetriebnahme und Grundlagen-Charakterisierung eines SDD (Silicon-Drift-Detector) für Messungen nach dem BIXS (Beta-Induced X-ray) Prinzipien und erste Messungen mit tritiiertem Wasser in Hinblick auf den endgültigen Einsatz des SDDs für die Online-Messung der Tritiumkonzentration in Wasser für die TRENTA-Anlage

Simone Rupp
Entwicklung einer Methode zur Messung der Quanteneffizienz von Laser Raman Systemen

Vera Schäfer
Test von optischen Beschichtungen auf Beständigkeit gegen Tritium

Fabian Schneck
Untersuchung des Adsorptionsverhaltens von Tritium an Oberflächen und Implikationen für KATRIN

Elisabeth Urbach*
Beurteilung der Messunsicherheit von mechanischen Prüfverfahren im kryogenen Umfeld

Bachelor Theses 2012 (*completed)

Moritz Bader*
Experimentelle Ermittlung von stationären, quasistationären und transienten Wärmeübergängen von elektrisch erwärmten supraleitenden Bandleitern in flüssigem Stickstoff

Sebastien Barbier*
Commissioning of an infrared camera for optical analysis of flow distributions in cryopanels

Viswanath Bharathwaj*
Measurement of temperature distribution in tube in tube heat exchanger coil using Fiber Bragg Grating sensors

Joachim Debatin
Untersuchung der Permeation von Gasgemischen durch neuartige Zeolite-Membrane

Julia Dusold
Charakterisierung eines Siliziumdriftdetektor-Systems

Sylvia Ebenhöch*
Simulation und experimentelle Arbeit an TriRex

Beate Frank*
Dynamische Messungen an Sicherheitsventilen

Nando Gramlich*
Parametrische Untersuchungen an einer Kaskade aus drei Membranreaktoren zum Austausch von Wasserstoffisotopen

Moritz Hackenjos*
Marktrecherche und Analyse handelsüblicher Komponenten für ein IR-Sensorsystem zur Konzentrationsbestimmung flüssiger Wasserstoffisotopologe im Umfeld der Fusionsforschung

Katharina Höveler*
Messung tritiuminduzierter Bremsstrahlung an TRIREX für KATRIN

Nadja Kästle*
Erstellung eines Marketingkonzepts in einem wissenschaftlichen Institut

Manuel Klein
Funktionsnachweiß eines Messsystems zur Bestimmung der Tritiumkonzentration in Wasser mittels Verstärkerfolie und Photodioden

Bennet Krasch*
Aufbau und Durchführung von Testexperimenten zur Fotoakustischen RAMAN Spektroskopie

Steffen Mundt*
Entwicklung einer interaktiven Softwarelösung zur Implementierung der KATRIN-Nummern in das Datenbanksystem

Julian Pfinder*
Konzeption eines Versuchsstandes zur präzisen Untersuchung von Massenstromsensoren

Manuel Pitsch*
Potentialanalyse regenerativer Energien zur Eigenversorgung von Versorgungsgebieten

Florian Schleißinger*
Winkelabhängige E(I)-Messungen an technischen HTS-Bandleitern

Michael Schmidt*
Aufbau einer Messstrecke zum Test eines neuen Sensors zur Positionsbestimmung eines kryogenen Kompaktventils

Sebastian Schüler*
Charakterisierung von Festkörper-Szintillatoren für den Einsatz zur Messung von Tritium in Wasser

Sascha Singer*
Migration der Steuerung einer Anlage zur Elektrolyse sowie Erstellung einer hierfür geeigneten Visualisierung

Pranay Valson*
Measurement of stress distribution in a high temperature superconductor tapes at cryogenic temperatures

Johannes Weis*
Bestimmung von Tritiumablagerungen auf einem vergoldeten Schwingquarz (TriQuarz)

Teaching and Education

ITEP Colloquies

24.01.2012 Charakterisierung von YBCO-Bandleitern für einen supraleitenden Strombegrenzer
Jürgen Hieringer; (Bachelorarbeit); SUPRA

08.03.2012 Winkelabhängige U (I)-Messungen an technischen HTS-Bandleitern
Florian Schleißinger; (Bachelorarbeit); HFM

03.04.2012 Erstellung eines Messunsicherheits-budgets für die kryogene Temperatur-messung
Michael Schrank; (Trainee); KRYO

17.04.2012 Model and Simulation of a HTS Generator under transient operation
Victor M. R. Zermeño; Technical University, Denmark; SUPRA

24.04.2012 Untersuchung der Sorption an Aktivkohle bei kryogenen Temperaturen
Sophie Sulzmann; (Studienarbeit); VAKUUM

25.04.2012 High-temperature superconducting Conductor on Round Core (CORC) cables for power transmission and magnet applications
Danko van der Laan; University of Colorado (Boulder); FUSION

08.05.2012 Production and Characterisation of HTS Roebel cable
Nicholas Long; Industrial Research, New Zealand; SUPRA

09.05.2012 Untersuchungen zum Potential von Photovoltaik und Windkraft am KIT/CN Nord
Manuel Pitsch; (Bachelorarbeit); SUPRA

23.05.2012 Theoretische und experimentelle Untersuchungen zur Stabilität von Hochtemperatur-Supraleitern
Olaf Mäder; (Doktorarbeit); SUPRA

19.06.2012 Charakterisierung einer Quecksilber-diffusionspumpe für den Einsatz in einem Fusionskraftwerk
Benedikt Peters; (Studienarbeit); VAKUUM

26.06.2012 Status der KATRIN-Transportstrecke
Woosik Gil; KATRIN

17.07.2012 Design eines HTS-Solenoiden
Alexander PolloK; (Diplomarbeit); HFM

24.07.2012 Calorimetry at TLK – measuring the heat of tritium
Alecu Catalin; TLK

31.08.2012 Development of YBCO Twisted Stacked-Tape Conductor at MIT
Makoto Takayasu; MIT; FUSION

04.10.2012 Aufbau einer Apparatur zur Untersuchung des Einflusses von Flux-Pinning auf den kritischen Strom technischer Hochtemperatursupraleiter
Christoph Bayer; (Diplomarbeit); FUSION

04.10.2012 Fatigue properties of titanium alloys at cryogenic temperatures
Yoshinori Ono; Institute for Materials Science (NIMS); FUSION

16.10.2012 Introduction of Laboratory and Research Status on Hanyang University
Wooju Shin; Hanyang University, Korea; SUPRA

18.10.2012 The present state of development of 154 kV SFCL at KEPCO-RI
Heesun Kim KEPCO; Korea; SUPRA

08.11.2012 General overview of the Quench Protection Circuit for JT-60SA Satellite Tokamak
Alberto Maistrello; Consorzio RFX, Euratom-ENEA Association; FUSION

20.11.2012 Vorlesung: Calibration of vacuum gauges
Wolfgang Jitschin; Hochschule Mittelhessen; VAKUUM

22.11.2012 Determination of the critical current density of HTS tape
Julien Leclerc; University of Lorraine, GREEN laboratory; SUPRA

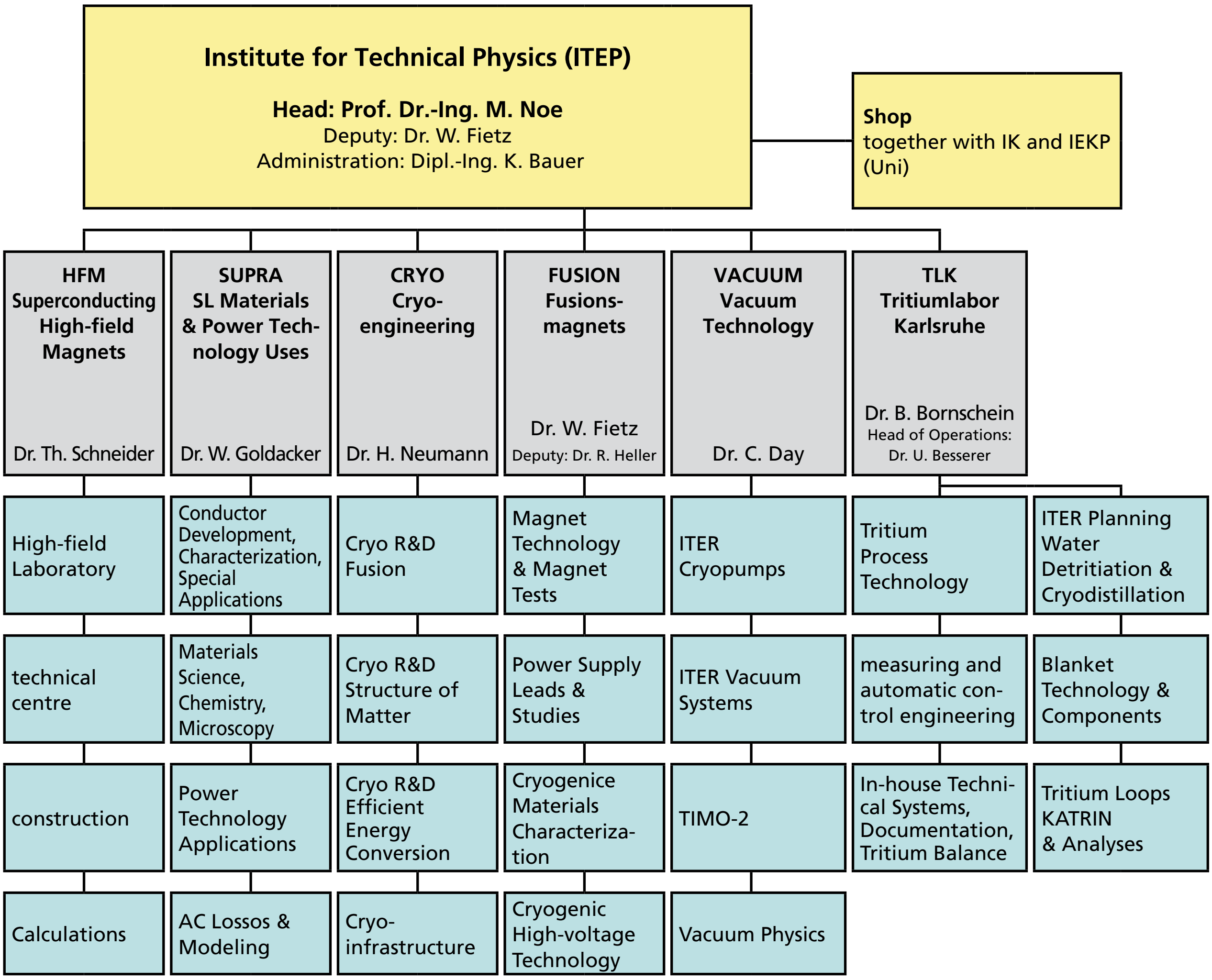
27.11.2012 Erstellung eines Marketingkonzepts in einem wissenschaftlichen Institut
Nadja Kästle; (Bachelorarbeit); Administration

04.12.2012 Gasdurchflussmessung in der Kryotechnik
Michael Schrank; (Trainee); KRYO

14.12.2012 Experimentelle Ermittlung des Wärmeübergangs an Bandleitern in flüssigem Stickstoff
Moritz Bader; (Bachelorarbeit); SUPRA

Figures and Data

ITEP Chart of Organization (January, 2012)



Personnel Status (30.11.2012)

Total	**197**	Apprentices	1
University graduates	55	Trainees	7
Engineers and technicians	62	**additionally, during 2012**	
Others	32	Guests	10
Pre-doctoral students	18	Trainees	15
Diploma students	9	Student assistants	18
DH students	13	Term Papers, bachelor theses	23

Figures and Data

Personnel Changes in 2012

Leaving (Excluding Trainees, Guests, and Student Assistants)

Isabelle Ehleben

Dr. Olaf Mäder

Christoph Plusczyk

Sebastian Heuser

Beate Frank

Steffen Mundt

Harald Moosmann

Ioan-Catalin Petrutiu

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

Alexander Beck

Joachim Debatin

Eduard Demencik

Miroslav Dimov

Julia Dusold

Patthabi Vishnuvardhan Gade

Sabrina Gerl

Cristian Gleason-González

Nando Gramlich

Amit Grover

Carolin Heidt

Sebastian Hellmann

Nadja Kästle

Lisa Marie Maurer

Martin Meinzer

Simon Niemes

Cathrin Röhnisch

Simone Rupp

Vera Schäfer

Michael Schmidt

Fabian Schneck

Katelijne Vandemeulebroucke

Victor Zermeno

Figures and Data

Trainee / Student assistants

Trainee 2012 (* completed)

Katharina Battes

Andras Bükki-Deme

Thomas Giegerich

Xavier Lefebvre

Santiago Ochoa Guamán

Christoph Plusczyk

Michael Schrank

Student assistants 2012

Daniel Barth

Christoph Bayer

Sebastian Della Bona

Christopher Franke

Sebastian Hellmann

Jürgen Hieringer

Till Holzhäuser

Pascal Kraft

Simon Kudella

Sebastian Mirz

Franz Möltgen

Simon Niemes

Manuel Pitsch

Toni Quach

Clio Saglietti

Matthias Schaufelberger

Florian Schleißinger

Jasmin Seeger

Figures and Data

Guest Researcher

Guest Researcher

Prof. Dr. Bruno Douine
15.09.–31.12.12 Université de Lorraine, Nancy, Frankreich

Kim Heesum
15.10.–18.10.12 KEPCO, Korea

Prof. Kenzo Munakata
25.06.–29.06.12 Akita University, Japan
17.09.–21.09.12 Akita University, Japan

Silvia Napoli
23.–27.04.2012 Universität Swansea, UK

Alina Niculescu
11.06.–31.07.12 National Institute of R&D for Cryogenic and Isotopic Technologies, Institut ICIT, RM Vilcea, Rumänien

George Okoth
13.08.–19.10.12 Universität Bremen, Deutschland

Dr. Hossain Shahriar
21.05.–15.06.12 University of Wollongong, Australien

Prof. Dr. Frédéric Sirois
22.10.–31.12.12 École Polytechnique de Montréal, Kanada

Dr. Makoto Takayasu
27.08.–31.08.12 Massachusetts Insititute of Technology, Cambridge, USA

Prof. Richard Taylor
16.04.–20.04.12 Queensland University of Technology, Australien

Dr. Danko van der Laan
23.04.–27.04.12 University of Colorado (Boulder), USA

Shin Wooju
15.10.–18.10.12 Hanyang Universität, Korea

Figures and Data

Membership in Relevant Technical and Scientific Organizations

Kai Bauer

- Member of the Helmholtz Management Academy
- Member of the „Arbeitssicherheit und Umweltschutz" working group
- Member of the committee of culture of study at the Baden-Wurttemberg Cooperative State University Karlsruhe
- Member of the examination board of the Baden-Württemberg Cooperative State University Karlsruhe in the programmes Mechanical Engineering and Business & Engineering

Beate Bornschein

- Member of the „International Steering Committee" of the „International conference on Tritium Science and Technology"
- Member of the „Executive Committee of IEA Nuclear Technology for Fusion Reactors Network Co-ordinator for EU network trainee programme 'TRI-TOFY'
- Member of the KATRIN Executive Committee
- Member of the KATRIN Collaboration Board
- Coordinator Source and Transport Section of KATRIN
- Member of the Scientific Technical Assembly of KCETA
- Member of the Executive Board of KSETA (KHYS-Steering Committee)

Ion Cristescu

- Manager of cooperation TriPla-CA Consortium

David Demange

- Member of the Expert Panel for the Preliminary Design Review of the IFMIF/EVEDA Liquid Breeder Validation and the Tritium Release Modules

Christian Day

- Member of the Executive Board of the German Vacuum Society (DVG)
- Vice-chair of the „Fachverband Vakuumphysik und -technik der Dt. Physikalischen Gesellschaft (DPG)"
- Technical Consultant „Technology" of the European fusion programme's Director
- Co-ordinator of the VACU-TEC Goal oriented Training Programme, EFDA (GOT).
- Spokesperson Topic „Vakuum und Tritium", Deutsche DEMO Initiative
- Rarefied Gas Dynamics Conference Series, member in the International Advisory Committee
- International Symposium of Fusion Nuclear Technology, Member of the International Programme Committee (ISFNT)
- Associated Expert of the Indian Vacuum Society (IVS)
- Chartered Engineer of American Vacuum Society (AVS)

Wilfried Goldacker

- Vice-President of Board of Directors ICMC International Cryogenics Material Conf. (ICMC)
- Programme Board Member ICSM-Conf. Antalya, Turkey
- Member of Advisory Board of Turkisch Centre for Superconductivity – Ankara
- Member of the Commission „Elektrotechnik Elektronik Informationstechnik" at DIN und VDE Referat K 184 "Supraleiter"

Steffen Grohmann

- Appointment on the W3 Professorship „Kälte- und Kryotechnik" at the „Institut für Technische Thermodynamik und Kältetechnik" of KIT
- Vice-chairman of „Normenausschuss NA 016-00-07 AA „Flüssighelium-Druckbehälter-Sicherheitseinrichtungen gegen Drucküberschreitung"
- Member of the „Verein zur Förderung der Luft- und Kältetechnik e.V."
- Member of the KATRIN Executive Board and KATRIN Publications Committee
- Member of the Institute of Refrigeration (IIF/IIR), Commission A1: Cryophysics, Cryoengineering

Volker Hauer

- Co-ordinator of the field "Fuel Cycle Modelling" of the European ITER-physics programme

Reinhard Heller

- Applied Superconductivity Conference, Member of International Programme Committee
- Applied Superconductivity Conference, elected Board member Large Scale
- Magnet Technology Conference, Member of International Programme Committee
- Computation of Thermo-Hydraulic Transients in Superconductors (CHATS-AS), Board member
- DKE/DIN K 184 – Superconductor
- International Electrotechnical Commission (IEC TC90) – Superconductivity – Member WG 12 – "Superconducting Power Devices-General Requirements for Characteristic Tests of Current Leads designed for Powering Superconducting Devices"

Holger Neumann

- Board member of the „Deutscher Kälte- und Klimatechnischer Verein e.V. – DKV"

Mathias Noe

- President of the European Society for Applied Superconductivity (ESAS)
- International Council of Large Electric Systems (CIGRE) Convenor of working group D.1.38 „Emerging Test Techniques Common to High Temperature Superconducting (HTS) Power Applications”
- International Council of Large Electric Systems (CIGRE) Member of working group D.3.23 „Application and feasibility of fault current limiters in power systems”
- International Energy Agency, Implementing Agreement for a co-operative programme for assessing the impacts of high-temperature superconductivity on the electric power sector, German representative
- Fusion for Energy (F4E) – Member of Technical Advisory Panel
- Member of the Association Steering Committee Euratom-KIT
- Karlsruhe school of Elementary and Astroparticle Physics, Member of Executive Board
- International Conference on Magnet Technology, Member of International Organizing and Scientific Programme Committee
- Applied Superconductivity Conference, Member of International Programme Committee
- European Conference on Applied Superconductivity, Member of International Programme Committee
- Programme Director of graduate programme Energy Engineering and Management of Hector School
- Advisory Panel of the periodical Physica C
- Editor IEEE Transactions on Applied Superconductivity, Editor for Large Scale Applications
- Smart Grid Platform Baden-Württemberg, participant
- Industrial Association Superconductors, Guest member
- Helmholtz Programme Efficient Energy Conversion and Use Programme, Spokesperson Topic Superconducting Components
- Member of Administrative Board of the „Heinrich-Hertz-Gesellschaft“
- KIT Energy Center, Member of the steering committee and Vice Spokesperson Energy Storage and Energy Distribution

Sonja Schlachter

- Member of the „Executive Board of Superconductor Science and Technology (SUST) in the Institute of Physics (IOP) UK“

Manfred Süßer

- Chairman of Standards Committee NA 016-00-07 AA „Flüssighelium-Druckbehälter – Sicherheitseinrichtungen gegen Drucküberschreitung“

Anne-Kathrin Weber

- Member of the KIT Convention
- Member of the examination board of the “Baden-Württemberg Cooperative State University Karlsruhe” in the Faculty Business Administration & Engineering

Klaus-Peter Weiss

- DKE – Deutsche Kommission Elektrotechnik Elektronik
- Vice-chairman Information Technology in DIN and VDE Department K 184 „Superconductors“
- Member of the IEC International Electrotechnical Commission/ Technical Comittee 90 „Superconductivity”
- Member of the Executive Committee of the International Research and Industrial Workshops MEM „Mechanical-Electromagnetic Properties of Superconducting Materials“
- Spokesman of the task force „Magnet Design” within the German coordination of Fusion-research for DEMO

Jürgen Wendel

- Founding member and longtime member of the executive board of the “Deutschen Gesellschaft für Flüssigszintillationschromatographie e.V. (DGfS)”, treasurer
- Course instructor at the Fortbildungszentrum für Technik und Umwelt (FTU) for the Programmes Radiation Protection and Radiochemistry

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* Alecu, C.G.; Besserer, U.; Bornschein, B.; Kloppe, B.; Köllö, Z.; Wendel, J.
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Vacuum Meeting (CroSloVM–19), Dubrovnik, HR, June 4–8, 2012

* Heiduk, M.; Bagrets, N.; Weiss, K.P.
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Kompatibilitätsexperiment von Turbomolekularpumpen mit Tritiumgas.
76. Jahrestagung der DPG und DPG-Frühjahrstagung, Fachverband Vakuumphysik und Vakuumtechnik,
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Wolf, J.; KATRIN Collaboration
The KATRIN neutrino mass experiment.
Internat.Symp.on Neutrino Physics and Beyond, Shenzhen, China, September 23–26, 2012

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Invited Papers

Beate Bornschein

- B. Bornschein, Tritium management and safety issues in ITER and DEMO breeding blankets, 27th Symposium on Fusion Technology (SOFT) 2012; in Liège, Belgien, vom 24.–28. September 2012

Christian Day

- Chr. Day, "What large vacuum systems can learn from micro gas flows – and vice versa", 1st European Conf. on Gas Microflows, Skiathos, Griechenland, Juni 2012.
- Chr. Day, Th. Giegerich, V. Hauer, X. Luo, St. Varoutis, "The use of flow network tools for geometrically complex vacuum gas dynamics problems", 6th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Wien, Österreich, September 2012.

Walter Henry Fietz

- W. H. Fietz "Prospects of High Temperature Superconductors for fusion magnets and power applications" 27th Symposium on Fusion Technology (SOFT), Liège, Belgium, September 24–28, 2012

Wilfried Goldacker

- W. Goldacker, S. I. Schlachter, A. Kario, A. Kling, F. Grilli, M. Vojenciak, Chr. Barth, A. Kudymow, HTS high current AC cables for applications, ICSM 2012 Istanbul
- W. Goldacker, Methods to reduce AC losses in Coated Conductors, Workshop supraleitende Motoren, Schloss Löwenstein, Miltenberg
- W. Goldacker, M. Noe, International development in superconducting motors, Workshop supraleitende Motoren, Schloss Löwenstein, Miltenberg

Francesco Grilli

- F. Grilli, P. Krüger, M. Vojenčiak, V. M. Rodriguez Zermeño, Numerical modeling tools for REBCO coated conductors, CCA2012 Conference on Coated Conductor for Application, Heidelberg

Steffen Grohmann

- S. Grohmann, V. Hannen, J. Wolf,
Neutrino Mass Measurement with the KATRIN Experiment. In: Berghoefer T, editor. 3rd ASPERA Technology Forum. Darmstadt, Germany: Astroparticle Physics ERA-Net; 2012. p. 14–9.

Stefan Hanke

- St. Hanke, "The development of the unique and large cryopump systems for the heating neutral beam injection system of ITER", Int. Symp. on Vacuum Science and Technology and its Applications to Accelerators (IVS 2012), Kolkata, Indien, Februar 2012.
- St. Hanke, "Development of a large customized NBI cryopump system", 20th Topical Meeting on the development of Fusion Energy (TOFE 2012), Nashville, TN, USA, August 2012.

Anna Kario

- A. Kario, W. Häßler, C. Rodig, M. Schubert, J. Scheiter, B. Holzapfel, L. Schultz , R. Nast, S. I. Schlachter, W. Goldacker: P. Kovac, T. Melisek, High energy milled ex situ MgB_2 as precursor for superconducting tapes, Warsaw, 4. april 2012, Institute of high pressure, Polish Academy of Science

Mathias Noe

- M. Noe, E. Marzahn „Hochtemperatur-Supraleiter Kabel", 79. Kabelseminar, 28.–29. Februar 2012, Leibniz Universität Hannover
- M. Noe „Ökonomie und Effizienz Supraleitender Systeme", Zukunft und Innovation der Energietechnik mit Hochtemperatur-Supraleitern, 6.–7. März 2012, Beethovenhalle Bonn
- M. Noe „Widerstand zwecklos – Supraleiter erobern Smart Grids, KIT Business Club, 12. April 2012
- M. Noe "Large Scale Applications of Superconductors", 3rd International Conference on Superconductivity and Magnetism, 29. April – 4. May 2012, Istanbul, Turkey
- M. Noe, "Superconducting Fault Current Limiters, Superconducting Transformers and Cryogenic Electrical Insulation", ESAS Summer School on Superconductivity 2012, June 11–15, 2012 at Lens en Vercors, Frankreich
- M. Noe, "HTS Power Applications in the US", Workshop on Present Status and Future Perspectives of HTS Power Applications", CIGRE SCD1.38, 29. August 2012, Paris
- M. Noe, "R&D Status of HTS Power Applications in Europe", Dasan Conference on Superconductivity, 7.–9. November 2012, Jeju Island, Korea

Santiago Ochoa Guamán

- S. Ochoa Guamán, "Vacuum systems of fusion power plants", Kollegium der Universität Guayaquil, Ecuador, Dezember 2012.

Klaus-Peter Weiss

- K.-P. Weiss, "CryoMaK – an Overview" Presented at Chinese Academy of Science, Institute of Technical Physics and Chemistry, Beijing, China, 23.8.2012
- K.-P. Weiss Institute of Plasma Physic, Hefei, China, 24. August 2012

Rainer Nast

- R. Nast, B. Ringsdorf, A. Jung, B. Runtsch, M. Vojenciak, A. Kario, W. Goldacker, T. Holubek, S. Casalbuoni, Effects of laser structuring on the properties of (RE) BCO coated conductors, CCA2012 Conference on Coated Conductor for Application, Heidelberg

Magnus Schlösser

- M. Schlösser, Was hat ein grüner Laserstrahl mit der Neutrinomasse zu tun, Junge Talente, Wissenschaft und Musik am 16. Februar 2012 und VDE Bezirksverein Mittelbaden am 24. April 2012

Victor Zermeno

- V. Zermeno, A. B. Abrahamsen, N. Mijatovic, B. B. Jensen, M. P. Sørensen, Calculation of AC losses in large HTS stacks and coils, CCA2012 Conference on Coated Conductor for Application, Heidelberg

Publications

Patents Held

* Neue Schutzrechtsanmeldungen in 2012
** Schutzrechtserteilungen mit Wirkung für Deutschland in 2012

Strombegrenzer mit elektrischen Ventilen zum Begrenzen des Kurzschlussstromes in einem elektrischen Leistungsstromkreis
Jüngst, Klaus-Peter; Kuperman, Grigory
DE 1149452
US 6654222

Verfahren zur Steuerung der Netzgeräte zum Laden der Energiespeicher eines Leistungsmodulators und Leistungsmodulator zur Durchführung des Verfahrens
Jüngst, Klaus-Peter; Kuperman, Grigory
DE 10036519

Flacher, aus elektrisch leitenden Strängen zusammengesetzter verlustarmer elektrischer Leiter
Klimenko, Evgueni
DE 1349183

Zusätzliche Einrichtung in einem Strombegrenzer zur Strombegrenzung im Fehlerfall
Jüngst, Klaus-Peter; Kuperman, Grigory; Noe, Mathias
CA 2577435
CN 2005800416707
DE 102004058633
EP 05791533.2-1231
US 7327542

Planar-helischer Undulator
Beckenbach, Max; Eisele, Matthias; Kläser, Marion; Leys, Pauline; Lott, Bernd; Schneider, Theo
DE 102006056052
US 8134440

Kryostat mit einem Magnetspulensystem, das eine LTS- und eine gekapselte HTS-Sektion umfasst
Kläser, Marion
DE 102006012508
EP 07723071.2-1231
US 8255023

Kryostat mit einem Magnetspulensystem, das eine unterkühlte LTS- u. eine in einem separaten Heliumtank angeordnete HTS-Sektion umfasst
Schneider, Theo
CH 1999764
DE 102006012511
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Anlage zur supraleitenden magnetischen Energiespeicherung, elektrolytischen Wasserzerlegung und wassersynthetisierenden Strombegrenzer
Gehring, Rainer; Sander, Michael
DE 102007042711

Mit einer Kühlschicht versehener hochtemperatursupraleitender Bandleiterverbund
Schacherer, Christian; Schwarz, Michael
US 12/809,133

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DE 102008053679
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Drechsler, Antje; Goldacker, Wilfried; Oomen, Marijn; Rabbers, Jakob Johan; Schlachter, Sonja
DE 102009043580.8-34

Vorrichtung zur Strombegrenzung mit einer veränderbaren Spulenimpedanz
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