Development of superconducting and cryogenic technology in the Institute for Technical Physics (ITP) of the Research Center Karlsruhe

W. Goldacker, R. Heller, A. Hofmann, F. Hornung, K.P. Jüngst, W. Lehmann, A. Mack, H. Neumann, A. Nyilas, B. Obst, Th. Schneider, A. Ulbricht *, H. Wühl

Forschungszentrum Karlsruhe, Institut fur Technische Physik, Hermann von Helmholtz Platz 1, D 76344 Eggenstein Leopoldshafen, Germany

Dedicated to Prof. P. Komarek on the occasion of his 60th birthday November 2001

Abstract

Since the early 1970s the Institute for Technical Physics of the Research Center Karlsruhe has been involved in the development of superconductivity for research and industrial applications. A broad program with a focus on the superconducting magnet technology was established to include large magnets for nuclear fusion, high field magnets for nuclear magnetic resonance spec trometers, ore separation and energy storage magnets. Research and development work was performed in collaborative projects with other national as well as international institutions and industry. The success of these projects has been supported by a broad foundation of engineering science in superconductor development, electrical and cryogenic engineering. Several well known test facilities like TOSKA, STAR, HOMER, MTA along with well equipped laboratories for conductor development, materials at cryogenic temperatures, cryogenic high voltage engineering have made substantial contributions to in house, national and inter national projects. A strong cryogenic infrastructure with two refrigerators and sophisticated cooling circuits from about 4.5 K down to 1.8 K assure the reliable operation of these large facilities. Last but not least, cryogenic research, including vacuum pumps for International Thermonuclear Experimental Reactor, improvements in thermal insulation, cryogenic instrumentation and small on board refrigerators has supported progress in this field. High temperature superconductivity projects for low AC loss conductors, a 70 kA current lead and a fault current limiter are currently in progress.

Keywords: Structural materials, superconductors (A); He II systems, pumps (E); Power application; Superconducting magnets (F)

Contents

* Corresponding author. Address: Forschungszentrum Karlsruhe, Institut fur Technische Physik, Postfach 3640, Karlsruhe 76021, Germany. Tel.: +49 7247 82 3911; fax: +49 7247 82 2849.

E mail address: albert.ulbricht@itp.fzk.de (A. Ulbricht).

1. Introduction

At the beginning of the 1970s superconducting low-temperature technology had progressed far enough that the application in research and industry was near at hand. Large superconducting magnets for bubble chambers and special beam transport magnets for high-energy physics were under construction. The required high-magnetic fields or magnetic fields in large volumes, which could not be economically generated by existing normal magnet technology, were a challenge for the superconducting technology.

Since this period, the Institute for Technical Physics (ITP) has grown to be one of the largest institutions in

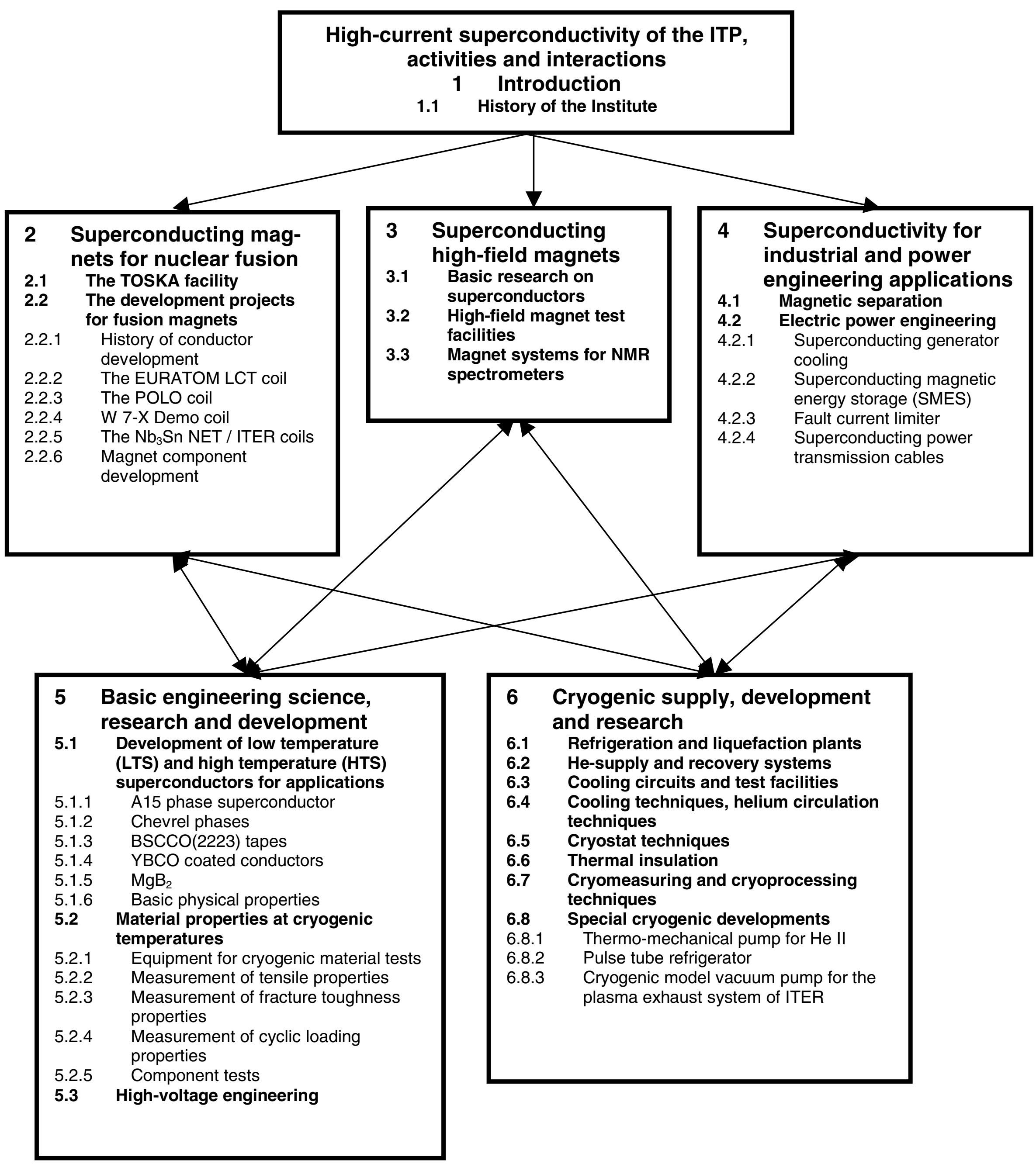
Europe, within the broad area of research and development in applied superconductivity. The main goal has been to make superconducting technology available in fields that require it and where continuous research and development has been necessary for breakthroughs making superconducting components economical.

This review reflects ITP's achievements in research and development work in different fields over 30 years and the existing potential of the Institute in applied superconductivity. An overview of the activities is given in Table 1.

1.1. History of the Institute

In the beginning, the basic unit of ITP was part of the "Institute for Experimental Nuclear Physics (IEKP)" headed by W. Heinz, as one of the three directors of the IEKP who initiated the development of superconducting

Table 1
High current superconductivity activities of the Institute for Technical Physics



accelerator magnets. The cryogenic infrastructure was already under development and construction due to the goal of the other two directors, A. Citron and H. Schopper, to have the first linear proton accelerator and a particle separator with superconducting cavities. The development of superconducting accelerator magnets was being done in collaboration with European industry and other European laboratories in order to prepare the technology of superconducting magnets for the CERN superproton synchrotron (SPS). The decision of the CERN council to construct the SPS magnets with normal copper conductors forced the superconducting magnet section to base their research activities on broader topics. At this time P. Komarek joined the institute and became head of the superconducting magnet section (1973). The research activities were expanded to enable the section to manage larger projects in the field of superconducting magnet technology. These include research in technical superconductors, metallic and non-metallic structural materials, electrical engineering, cryogenic engineering, computer code development, and project studies, as well as basic research in superconductor and low-temperature physics. Projects were initiated in collaboration with industry and other institutions for industrial application of superconducting technology in energy technology (e.g. cable, generator, superconducting magnetic energy storage (SMES), and nuclear fusion) and other areas (magnetic separation, high-field magnets, and nuclear magnetic resonance (NMR)). The participation in the Large Coil Task (LCT), a project of the International Energy Agency (IEA) for the development of superconducting magnets for nuclear fusion, was the beginning of large size superconducting magnet technology, which has continued along these lines up to the International Thermonuclear Experimental Reactor (ITER) model coils, which are the largest research and development area of the Institute. The activities of the seventies and the first half of the eighties have been described in [1]. The superconducting magnet section of the IEKP became the "Institute for Technical Physics" in 1977 with W. Heinz as director. After the death of W. Heinz in 1984, P. Komarek took on the responsibilities for the Institute and became the official director of the ITP in 1986.

Some of the most important highlights of the Institute are:

- Nuclear fusion magnet development with the Toroidale Spulentestanlage Karlsruhe (TOSKA) magnet test facility and the test of several superconducting magnets (EURATOM LCT coil, poloidal field model coil (POLO), Wendelstein 7-X demonstration coil (W 7-X DEMO coil), and the ITER toroidal field model coil (TFMC)). These projects have been essential contributions to both conductor development and magnet technology along with large sized cryogenics in the application of superconducting magnet systems to nuclear fusion.
- In collaboration with industry, the development of high-field magnets with its test facilities (JUMBO, HOMER I, MTA) has contributed to the commercial availability of high-quality superconducting magnets for 750, 800 and 900 MHz NMR spectrometers with corresponding field levels of 17.6, 18.8 and 21.2 T.
- Superconducting magnets for ore separation achieved industrial application and a superconducting magnet for electrical network compensation (SMES) demonstrated its efficiency in a field test.

The success of these projects has been based on accompanying engineering science research and the development of suitable test facilities in the following fields:

- Superconductor and superconducting composite development.
- Cryogenic material investigations.
- Cryogenic high-voltage engineering and component development.
- Cryogenic engineering, low-temperature physics and infrastructure: These include refrigeration and helium supply as well as developments in cooling, cooling circuits and systems, test facilities and control systems.

In 1998 the fusion oriented vacuum pump section has been integrated into the ITP, using the cryogenic infrastructure for the development of a model vacuum pump for ITER in the Test Facility for ITER Model pump (TIMO).

The discovery of high-temperature superconductors (HTS) in 1986 switched the activities in superconductor physics and conductor development completely into this new field. New collaborations and projects were initiated, especially in power engineering (e.g. low AC loss conductors for electrical power components).

The basis of engineering science of the Institute's research and development (R&D) program is described in a book by P. Komarek [2].

2. Superconducting magnets for nuclear fusion

These activities have been performed by an interaction between design studies of fusion reactors and the experimental program, which supports both the toroidal and poloidal magnet development. The superconducting fusion magnet activities have been performed in two areas:

(1) Participation in reactor magnet design studies, design of model or prototype magnets as well as the design of test configurations.

These include computation of magnetic fields and forces along with design optimization of conductors and magnets, for projects (Tandem Spiegelmaschine Karlsruhe (TASKA) [3], International Tokamak Reactor (INTOR) [4], Next European Torus (NET) [5], Wendelstein 7-X (W 7-X) [6], and ITER/Conceptual Design activities [7]/Engineering Design Activities (EDA) [8]). Further details are given below in the project descriptions.

(2) Participation in hardware projects, including the design, construction and test of model or prototype magnets [9,10]. This means the development of the engineering technology of superconducting magnets together with industry and the confirmation in a representative overall test.

The development steps are characterized by the following projects:

- Participation in the "LCT" for developing toroidal field coils for tokamaks. The Institute helped to develop one of six D-shaped superconducting magnets, the EURATOM LCT coil (tests 1984 1987).
- The POLO project for developing poloidal field coils for tokamaks (tests 1994 1995).
- Demonstration of forced-flow superfluid He II cooling of the EURATOM LCT coil and operation of its NbTi technology at the maximum field levels (tests 1996 1997).
- Test of a superconducting stellarator W 7-X DEMO coil in the background field of the EURATOM LCT coil as a demonstration of technology for the W 7-X torus coils (1999).
- Test of the ITER TFMC as single coil and in the background field of the EURATOM LCT coil confirming the validity of the design (2001 2002).

For the first three projects, the responsibility was completely in the hands of the Research Center Karlsruhe. For the last two, the responsibility for coil design and construction was with Max-Planck-Institut für Plasmaphysik (IPP) and European Fusion Design Agreement/Close Support Unit (EFDA/CSU, former NET Team) both located in Garching, Germany respectively. The Research Center Karlsruhe contributed here to the coil design and construction and supported in component development. All the work was performed within the framework of the Project Nuclear Fusion of the Research Center Karlsruhe and the EURATOM Fusion Programs.

The beginning of the investigation of toroidal field coil arrangements with D-shaped coils was the six coil laboratory torus TESPE [11]. The experiment was used to study the mechanical stability of a toroidal coil system and for investigations of magnet safety [12,13]. Later on, the coils were rearranged in a linear system using four coils as background field for testing the W 7-X conductor, wound in test coils. Four such coils were tested in this so-called STAR facility [14,15].

The first activity for the development of large superconducting magnets for fusion was the participation of the Research Center Karlsruhe, represented by ITP, in the LCT. The LCT was initiated as a technology task in the mid-1970s for the development of large superconducting coils for the toroidal field magnet of tokamak machines. The task was performed under the auspices of the IEA with the participation of EURATOM, Japan, Switzerland and USA [16]. On behalf of EURATOM, the Research Center Karlsruhe was in charge of designing one superconducting coil, the so-called EURATOM LCT coil, for the six coil torus. Since the final test of a superconducting magnet is indispensable for confirming the successful conclusion of the development, the TOSKA facility was constructed in 1979 1983 for testing large superconducting magnets. The EURATOM LCT coil was the first magnet tested in TOSKA before shipping to the USA.

2.1. The TOSKA facility

The schematic view of the TOSKA facility with its equipment in the present state is presented in Fig. 1. Starting from 1984, the facility was upgraded incrementally to fulfill the requirements of the various

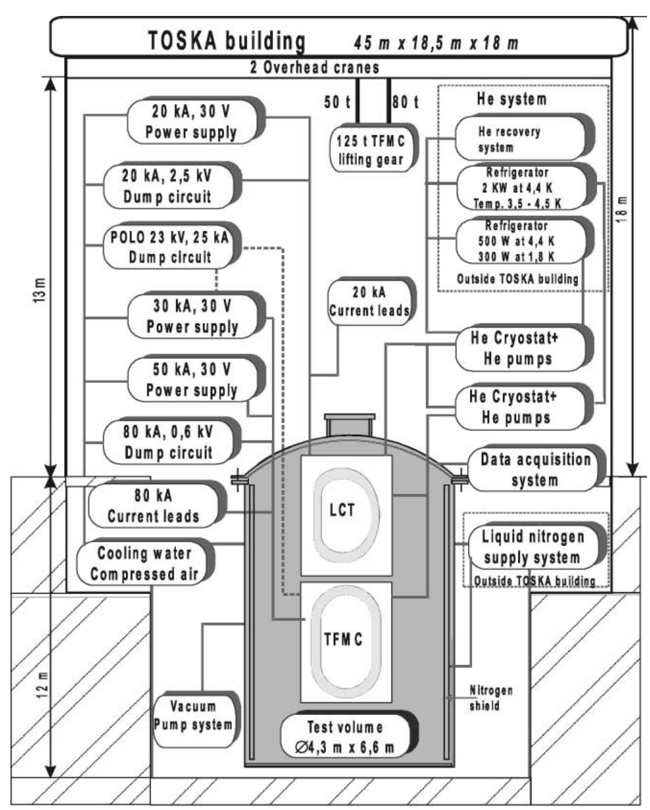


Fig. 1. Schematic view of the TOSKA facility with its components needed for testing the ITER TFMC.

Table 2
The rated voltage, current and energy for PS and SDC

Power supply/circuit	Voltage (V)	Current (kA)	Energy (MJ)
PS	30	20	
SDC	2500	20	300
PS	30	30	
HVDC	23,000	23	8
PS	30	80	
SDC	700	80	150

projects mentioned above until 2000 when it was ready for the test of the ITER TFMC [17]. The main components that have been added to the facility are:

- A 2 kW refrigerator with cold supply lines and valve box.
- A superfluid He II cooling circuit with cryostat, cold lines, piston, centrifugal and thermo-mechanical pumps for the helium circulation and using the Linde 300 W He II refrigerator.
- High-current power supplies (PS) and safety discharge circuits (SDC) as summarized in Table 2.
- Forced-flow-cooled 30 and 80 kA current leads.
- A crane system with a lifting capacity of 130 tonne.
- Modernized measuring and control as well as a data acquisition system.

All systems have worked very well during the test of the ITER TFMC test phase I (TFMC alone) with an availability of about 98%.

The TOSKA facility has been used effectively as the test bed for five successful superconducting magnet projects for fusion over a period of about 18 years and will be available for further component development for the ITER-FEAT construction phase.

2.2. The development projects for superconducting fusion magnets

Magnet component and fabrication development projects include the design and construction of conductor, winding and support structure of specific superconducting magnet types, including a final functional tests. The projects performed at the ITP are described in the following sections.

2.2.1. History of conductor development

A fundamental component of superconducting magnets is the conductor. The first coil design for the LCT was based on the well proven cryogenic stability criterion and NbTi as superconducting material [16]. It was also important for the requirements of the reactor design points to develop new technologies for the future. This perspective has led to forced-flow-cooled conductors, which allow a rigid winding pack, excellent dielectric insulation and a better matching of the conductor properties with the requirements of fusion reactor operation. The plasma physics request for magnetic fields as high as possible has pushed the worldwide development in the application of the A15 material Nb_3Sn and later on Nb_3Al by a Japanese group [18]. The A15 phase materials have allowed operational field levels of 13 T with sufficient margins for the constraints of tokamak operation.

In this advanced conductor development program, the ITP developed a forced-flow-cooled NbTi conductor for the EURATOM LCT magnet, a NbTi conductor for the poloidal field coils of a tokamak, a Nb_3Sn conductor for NET, and contributed the experience gained to the development of the ITER Nb_3Sn conductors.

A separate line of development was the NbTi cable-in-conduit conductor for the non-planar superconducting toroidal field coils of the stellarator W 7-X together with the IPP Garching.

2.2.2. The EURATOM LCT coil

The EURATOM LCT coil is a forced-flow-cooled NbTi coil with a D-shaped monolithic winding block, consisting of seven double pancakes enclosed in a stainless steel case with suitable elements for force transmission between winding and case [16]. The EURATOM LCT coil was developed in collaboration with German industry (Siemens, Krupp, Vacuumschmelze).

The basic design idea of the EURATOM LCT conductor was the creation of a rigid forced-flow-cooled conductor, allowing no strand movement and an optimal wetting of the strand surface by supercritical helium flow (Fig. 2) [19]. The conductor design was qualified by investigations of the forced-flow-cooling technique and conductor stability [20,21]. The conductor was industrially produced in a length of 7.5 km in pieces of about 500 m for the fabrication of the seven double pancakes of the coil winding.

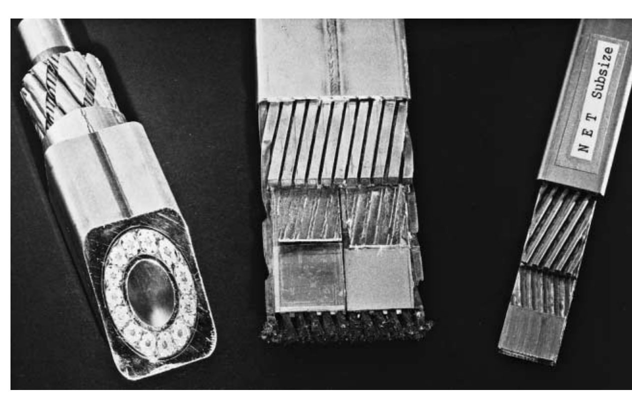


Fig. 2. Conductors developed for fusion magnets (NbTi conductors for the LCT (center) and POLO (left) coil, as well as subsize R&W Nb_3Sn NET conductor).

The EURATOM LCT coil ran successfully through its pre-test in the TOSKA facility, before shipping to the International Superconducting Fusion Magnet Test Facility at Oak Ridge National Laboratory, USA. In this facility, the EURATOM LCT coil was tested at the rated current level as a single coil as well as in the toroidal configuration with the five other coils. The toroidal configuration also included out-of-plane loading (one coil in the torus without current). For simulation of the field changes of the poloidal coils in a tokamak, the LCT coils were also exposed to magnetic pulse fields. In the single coil test as well as in the test in the toroidal configuration, the current of the test coil was raised to a value such that the forces were doubled on the test coil. Under these extended test conditions, the EURATOM LCT coil was operated stably at a magnetic field of 9 T, a temperature of 3.8 K and a conductor current of 16 kA in the single coil test. At this point, the coil was operated fully in the region of intrinsic stability with a Stekly factor α of about 10 (where for cryogenic stability $\alpha < 1$). In measurements of the current sharing temperature, it was confirmed that the coil achieved the critical data extrapolated from the strand critical data. These results were a breakthrough for forced-flow-cooled magnet technology, which has since been applied for large superconducting magnets with nearly no margin available or required for internal energy release, e.g. by friction of strands.

The excellent results were fully confirmed by the test of the mechanically reinforced EURATOM LCT coil in TOSKA by forced-flow-cooling with superfluid He II at a temperature of 1.8 K where the coil went normal at a predicted value of 19.6 kA and 11 T [22,23]. For the first time with such a large coil, He II was circulated by a thermo-mechanical pump working without moving parts [24] (see Section 6.8.1).

It was also demonstrated by this test sequence (reinforced single coil, coil in torus) that a single coil pre-test of a reinforced D-shaped coil can deliver appropriate performance data. This result is useful and can assure the proper function before the coil is installed in the toroidal configuration of a tokamak [25].

In He II operation, the mechanical stresses were comparable with those expected in operation together with the ITER TFMC. Based on these results, the coil was qualified to be used in further magnet development, delivering the background field in test configurations with prototype or model coils, as described later.

2.2.3. The POLO coil

The superconducting poloidal field coils for tokamaks are strongly linked to the dynamic requirements for driving and controlling the plasma current. Therefore, fast ramp rates, field changes during plasma control and transient fields by mutual coupling and during plasma disruption have to be absorbed without losing the superconducting properties. Fast ramping means a fast transfer of electrical energy, which requires high currents (POLO: 15 kA, ITER: 45 kA) and high voltages (POLO: 23 kV, ITER: 14 kV). The task of the POLO project was to develop the technology of superconducting poloidal field coils. At this time the specifications of the poloidal field coils of the superconducting tokamak TORE SUPRA were taken as a reference [26].

The POLO conductor was designed according to the pulsed requirements of the tokamak poloidal fields described above. Therefore, the applied NbTi strand was a mixed matrix Cu/CuNi low loss strand. In the two cabling stages, the strands and the subcables were respectively separated by resistive barriers in order to reduce the coupling losses. The structural material was integrated in a thick walled stainless steel jacket, which carried the coil hoop forces and had low eddy current losses (Fig. 2). The conductor was industrially produced in a total length of 600 m in pieces of 150 m.

The conductor had a dual cooling system. Two-phase helium was used in the central channel for removal of losses, keeping the temperature constant over the conductor length, and providing sufficient temperature margin in case of transient field changes. The annular space around the subcables was filled with supercritical stagnant helium for defined heat transfer in order to get sufficient transient conductor stability.

The POLO coil consisted of four solenoidal double pancakes with 3 m average diameter. It was designed to withstand high-voltage levels and transient field changes without losing the superconducting state [27]. Development and construction were carried out in collaboration with European industry (Alstom, Vacuumschmelze) (Fig. 3).

The coil was successfully tested in the TOSKA facility. For generating the high voltages and the fast field changes, a special counteracting current switch circuit was used. The crucial problem of ramp rate limitations caused by unbalanced current distribution in the subcables of the conductor was not observed. The excellent transposition achieved by the precise two stage cabling geometry and the careful joint design, resulted in a homogeneous inductance matrix between the subcables and kept a uniform current distribution among them during fast ramping and magnetic field transients. The homogeneity of the mutual inductances allowed typical 60 T/s field changes averaged over 20 ms. The quench current was only determined by the critical current of the cable. With these results, the basic technology of the superconducting poloidal field coils of a tokamak was successfully demonstrated.

2.2.4. W 7-X DEMO coil

For the large stellarator W 7-X of the Max-Planck-Institute for Plasma Physics (IPP) superconducting non-planar toroidal field coils are planned. The development

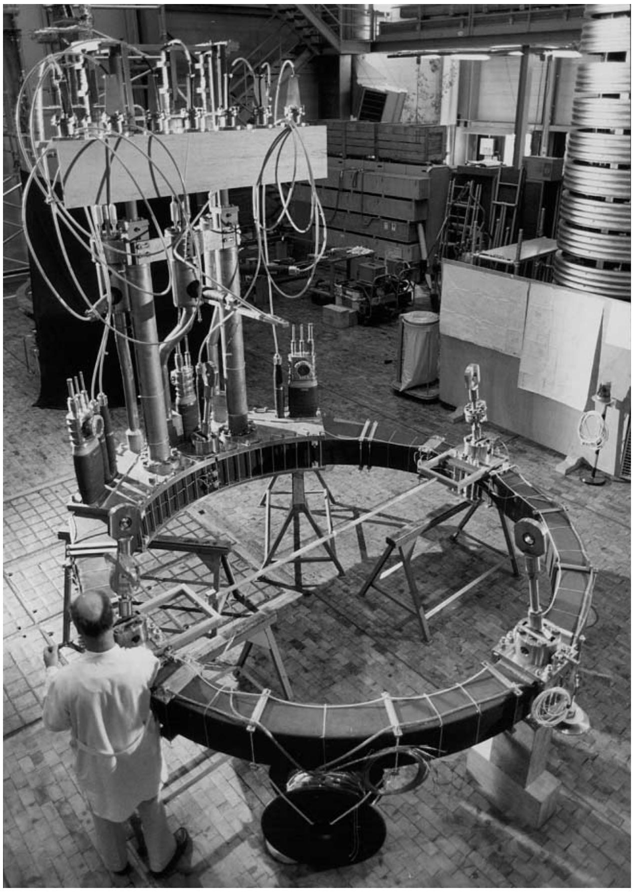


Fig. 3. The POLO coil during preparation for installation in the TOSKA vacuum vessel.

of such coils was carried out as a joint project of IPP with the Research Center Karlsruhe/ITP. This work included the conductor design and test (STAR facility), as well as the design, construction and test of a W 7-X DEMO coil.

The non-planar coils required a new conductor technology for making the fabrication of the winding not too difficult and expensive [15]. The solution developed was a superconducting cable, enclosed in an extruded seamless Al jacket. An Al alloy was selected, whose mechanical strength is increased by moderate heat treatment. Therefore the Al jacket is soft for the winding procedure and gets its final strength after the completion of the winding pack by a heat treatment (175 °C).

The construction of the W 7-X DEMO coil was performed in the European industry (Noell, Ansaldo) under the responsibility of the IPP Garching. The winding is embedded by sand filled resin in the coil case, which was fabricated from casted sections welded together. The coil was tested in the background field of the EURATOM LCT coil in the TOSKA facility for getting relevant field levels and mechanical stresses. The successful conclusion of the test confirmed the applied design principles and was the approval for starting the series production of the W 7-X toroidal field coils in industry [28,29].

2.2.5. The Nb_3Sn NET/ITER coils

Field levels of 12 14 T are required for future tokamak machines, as mentioned above. The brittleness of the A15 materials (Nb_3Sn, Nb_3Al) requires new strategies for the fabrication of windings in order to avoid conductor degradation. One solution is a suitable positioning of the heat treatment (about 650 °C, 200 h) for generation of the superconducting A15 phase during the production of the winding. Three procedures are candidates today:

React and wind (R&W), wind and react (W&R) and wind, react and transfer (W&R&Tr).

For the first design of the NET toroidal field coils, R&W conductors were foreseen. One such conductor was developed and tested as a subsize version in the ITP (Fig. 2) [30]. The conductor is a sandwich of a reacted Nb_3Sn Rutherford cable between two LCT Cu stabilizer cables enclosed in a stainless steel jacket. The strain dependence of the critical current of A15 materials leads to degradation, if materials in the composite conductors are not well matched with respect to thermal contraction.

A high-field conductor test facility, FBI, was developed to investigate these properties (Fig. 4a and b) [31]. This facility and the Cryogenic Material Laboratory (see Section 5.2) contribute substantially to the data base for the ITER central solenoid conductor (thick wall Incoloy 908 jacket) and the ITER toroidal field coil conductor (thin wall stainless steel jacket 316LN). Both ITER model coils were manufactured according to the W&R&Tr method. All handling procedures of reacted conductors during coil fabrication have to avoid strain levels that would cause irreversible degradation.

The arrangement of subcables for the ITER conductors was similar to that of the POLO conductor (Fig. 5). Both ITER conductors achieved the predicted critical currents in their model coils, according to the ITER design criteria.

The design and construction of the ITER TFMC was the task of the European Home Team (EUHT) as one of the large research and development projects of the ITER EDA.

The design of suitable test configurations for testing model coils fabricated from superconducting cables of the actual tokamak designs in the European Fusion Program (NET, ITER) was a continuous task, beginning in the mid-1980s [32,33]. The final test configuration of the ITER TFMC was fixed in 1995. The driving parameters were the achievement of relevant field and mechanical stress levels for acceptable cost, and fitting in the existing TOSKA facility. The test configuration selected has been placement of the ITER TFMC adjacent to the EURATOM LCT coil, linked by a suitable intercoil structure. For current levels of 70 kA (80 kA) in

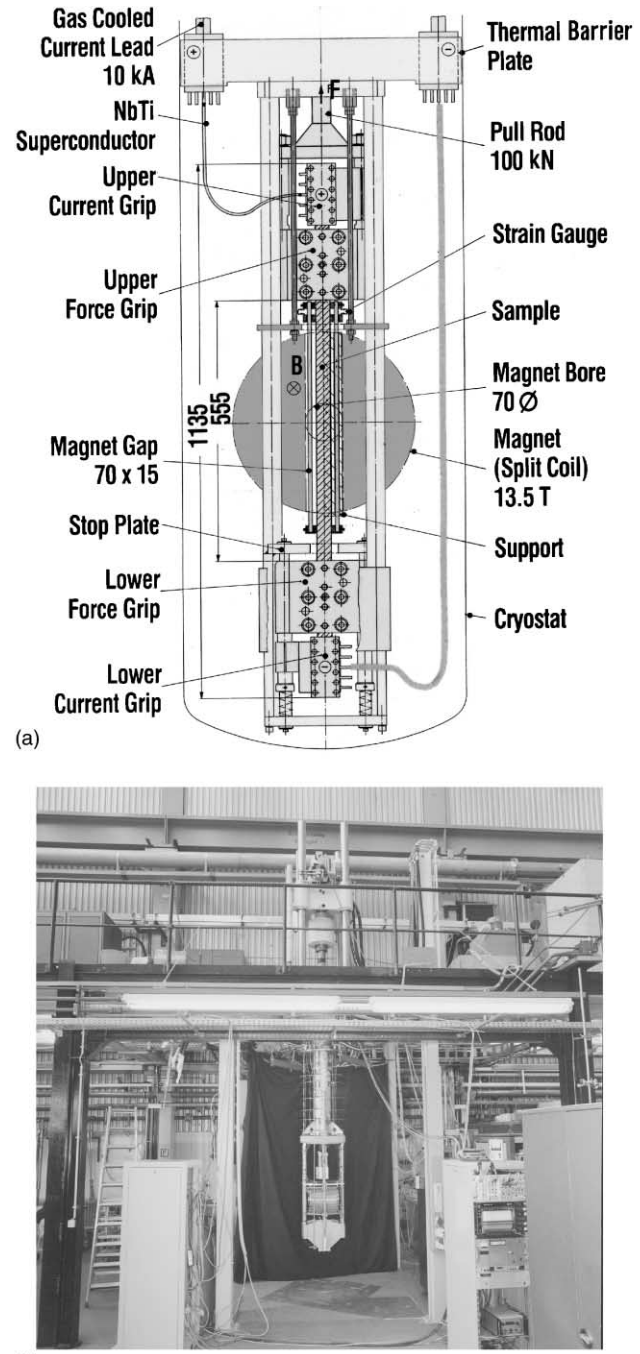


Fig. 4. (a) The construction principle of the high field conductor test facility, FBI, with a magnetic field up to 13 T and a pulling force up to 100 kN. (b) The high field test facility, FBI, in the laboratory; top: hydraulic pulling machine; bottom: magnet; the cryostat is lowered in the pit beneath the magnet.

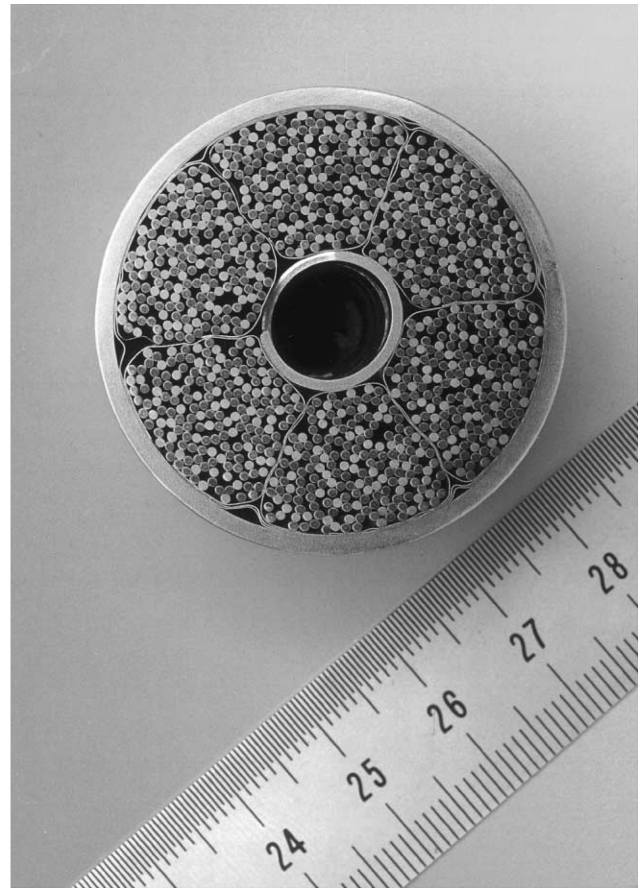


Fig. 5. The Nb_3Sn conductor of the ITER TFMC with a thin wall stainless steel jacket (Nb_3Sn strands: dark grey, Cu strands: light grey) [34].

the TFMC and 16 kA, in the LCT, a maximum magnetic field of 8.8 T (9.7 T) can be achieved [34].

The TFMC, using a Nb_3Sn conductor, was constructed by a European industry consortium (AGAN) under the guidance of EFDA/CSU (Garching) on behalf of the EURATOM. In particular, the Research Center Karlsruhe and the other EURATOM associated laboratories contributed to the conductor design and testing, material testing, component development and quality assurance [35]. The coil is made with a new winding method in which the Nb_3Sn conductors were spiral wound, heat treated, insulated and transferred into a spiral groove of a stainless steel radial plate, one on each side. Each radial plate contains two conductor spirals. Five radial plates were insulated, stacked, ground insulated and enclosed in a thick wall stainless steel case.

In the first experimental phase, the TFMC was tested as a single coil in the upgraded TOSKA facility (Fig. 6). The coil achieved 80 kA, which is the highest operating current ever used for such a coil. The test confirmed that the developed technology can be applied for the ITER FEAT toroidal field coils [36]. In the second test phase, the TFMC will be tested in the background field of the EURATOM LCT. This test will create stress levels in part of the TFMC that are relevant to those of the ITER toroidal field full size coils.

2.2.6. Magnet component development

In addition to the development of conductor and fabrication technology, discussed in the previous

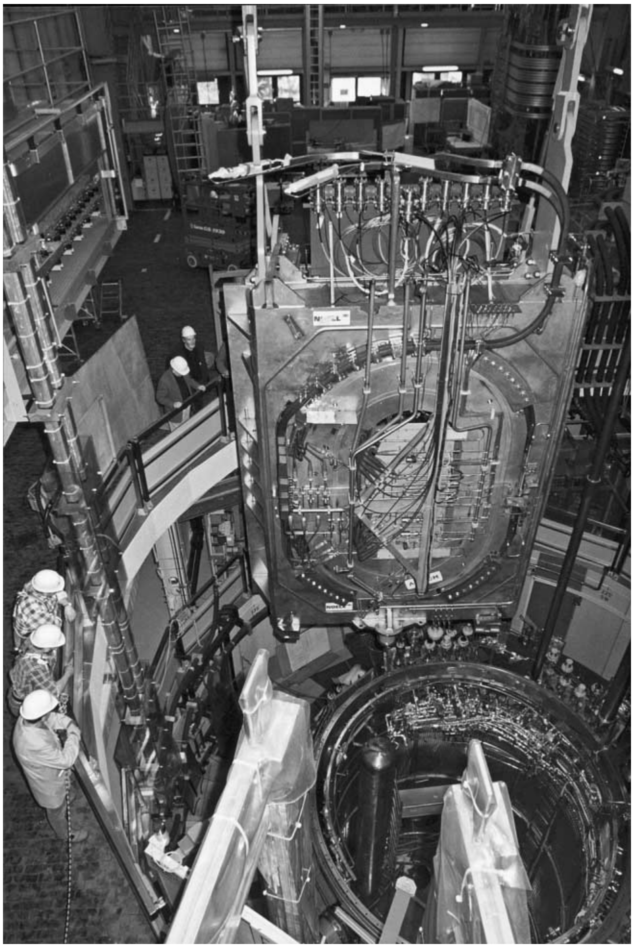


Fig. 6. The ITER TFMC during installation in the TOSKA vacuum vessel.

sections, conductor joints, electrical insulation system, quench protection and current leads are necessary for the operation according to the specific requirements of the coils. These areas require a separate development program.

For the EURATOM LCT coil, a full size joint and for the POLO coil, subcable joints were designed, constructed and tested in advance of full scale magnet tests. The electrical insulation system consists of the basic components (e.g. conductor insulation, insulation breaks, warm and cold feed-throughs, and instrumentation cables). These components have to be integrated into the magnet components like conductor terminals, current leads and instrumentation cabling lines. The basic components have to be pre-tested under actual operating conditions (pressure, leak, high-voltage insulation resistance) before installation in the magnet components [37]. The components of the electrical insulation system developed for the POLO coil were also used for the W 7-X DEMO coil and the ITER TFMC.

For protection of the superconducting magnets, suitable electronic circuits were developed applying the bridge circuit or a co-wound wire for compensation of the inductive voltage. This circuit has been indispensable for the fast and reliable detection of resistive conductor regions. For all magnets tested, the circuits worked very reliably with suitably adapted isolation amplifiers, which isolate the winding potential from the ground potential of the interlock system [27,38].

Along with providing the electrical insulation for the feed-through in the vacuum vessel, the current leads have also to conduct the current from the room temperature (RT) to 4 K with minimized thermal losses. In the POLO project, a forced-flow-cooled 30 kA current lead for 23 kV was developed. The helium heat exchanger (HEX) was optimized with the computer code CURLEAD [39]. Superconducting Nb_3Sn inserts were included in order to reduce the zero current losses and for better adapt for operation at various current levels. This type of current lead was successfully operated in vertical and horizontal positions for the POLO, EURATOM LCT and W 7-X coil tests. The design was extrapolated to an 80 kA current lead and a pair was

Fig. 7. The 20 kA HTS current lead with the HEX (inside the upper smooth tube), the two HTS modules and the contact surface to the superconducting bus bar (lowest section). In the background the re inforced EURATOM LCT coil can be seen.

constructed and successfully operated at these current levels during the test of the ITER TFMC.

Copper current leads are a considerable load for the cryogenic system. For the current lead operation, the electrical power of the refrigerator can be reduced by a factor of three by the application of high-T_C superconductors (HTS) at the cold end. A development program for so-called binary current leads (a conventional HEX with HTS cold end) was successfully concluded by the test of a 20 kA current lead in collaboration with National Institute of Fusion Science (NIFS), Japan (Fig. 7) [40]. As a next step, a 70 kA HTSC current lead will be designed, constructed and tested in TOSKA for ITER-FEAT [41].

3. Superconducting high-field magnets

For more than 20 years the High Magnetic Field Laboratory of the Institute for Technical Physics has been engaged in the development of superconducting high-field magnets. At present the activities concentrate on the following three areas:

- The conceptual design, construction, and operation of superconducting high-field magnet facilities.
- Basic research on advanced technical superconductors regarding critical current, n-value, stability, and quench propagation of these materials at 4.2 and 1.8 K.
- Design, construction and test of magnet systems for commercial NMR spectrometers. This work is done in cooperation with industrial partners.

Highlights of these efforts include the world record of 20.1 T for a superconducting magnet system achieved in 1987 [42] and the world's first 750 MHz [43] and 800 MHz NMR magnet systems built in 1991 and 1995, respectively. In 2001 a commercial 900 MHz NMR spectrometer was brought to market by the partner Bruker BioSpin GmbH.

3.1. Basic research on technical superconductors

Knowledge of the voltage current characteristics $V(I)$ of composite superconductors is very important for the development of superconducting high-field magnets, especially NMR magnets. These curves can be described by the empirical law $V(I) = V_C(I/I_C)^n$ where I_C is the critical current and the exponent is known as n-value. I_C and n were systematically investigated for the low-temperature superconductors (LTS) NbTi, $(NbX)_3Sn$ with additional components, X = Ta, Ti, and for Bi-2212/Bi-2223 composite HTS using the four-point measurement technique [44]. Only wires of highest performance were qualified for building high-frequency NMR magnet systems operated in persistent current mode with an

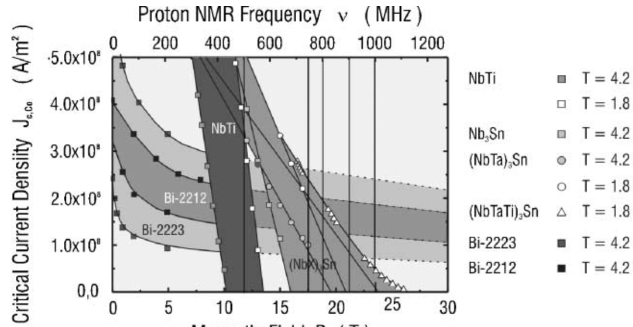


Fig. 8. Overall critical current density of various superconductors as a function of the magnetic field. The corresponding proton resonance frequencies are indicated at the top axis. The range for NbTi and the Nb_3Sn based materials is given by the J_C values at 4.2 K (closed symbols) and 1.8 K (open symbols). For the Bi 2212 and Bi 2223 tapes, the ranges indicate the scattering of the J_C values.

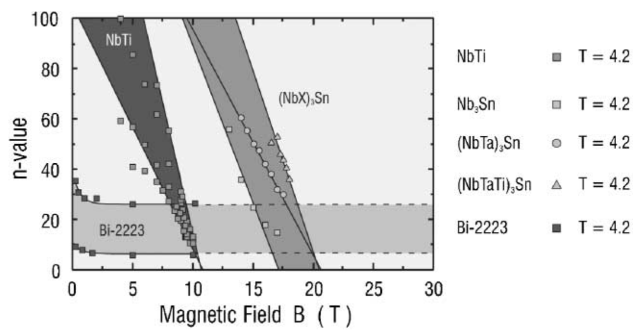


Fig. 9. n values at 4.2 K of various superconductors as a function of the magnetic field. The range for $(NbX)_3Sn$ is given by Nb_3Sn (□), $(NbTa)_3Sn$ (○), and $(NbTaTi)_3Sn$ (△). The ranges for NbTi and Bi 2223 indicate the scattering of their n values.

excellent combination of high spacial homogeneity and high temporal stability of the magnetic field.

The result of the work in the past years is given by Figs. 8 and 9. Fig. 8 shows the overall critical current density of various LTS and HTS superconductors as a function of external magnetic field. For clarification, the corresponding proton resonance frequency, where $\nu \propto B$, is also given. Insert coils made of HTS materials have to be used for NMR magnet systems with frequencies about 1000 MHz (23.5 T) and above.

The steepness n of the $V(I)$-characteristics is a measure of the structural homogeneity of a superconductor. Only materials showing the highest n-values are suitable for NMR magnet systems. From Fig. 9 one can see that the n-values of HTS have to be improved in order to use these wires in NMR magnet systems.

3.2. High-field magnet facilities

Basic research on LTS and HTS in magnetic fields up to 20 T presently use the facilities JUMBO and HOMER I at the High Magnetic Field Laboratory of the ITP. In order to achieve fields up to 25 T, a third facility, HOMER II, is under construction. The acceptance trials of the above mentioned series of NMR magnet systems are performed in the facility named MTA I [45]. To test NMR magnets of 1000 MHz and above, the facility MTA II is under construction.

JUMBO: The facility JUMBO is equipped with a magnet system consisting of superconducting NbTi- and Nb_3Sn-coils cooled in a liquid helium bath. Several configurations of coils are possible from 10 T in a 100 mm bore up to 15 T in a bore of 44 mm. Optionally, an inner cryostat can be installed to perform experiments in a range from 4.2 K up to ambient temperature.

HOMER I: HOMER I is an advanced facility for measurements in magnetic fields up to 20 T. HOMER I was the first facility equipped with a superconducting magnet system that reached 20.1 T [42]. To obtain such fields with LTS, the magnet system must be cooled down to 1.8 K. An overview of HOMER I is given in Fig. 10.

HOMER II: The facility HOMER II is currently under construction. The goal of the first phase is a magnetic field of 20 T in a 180 mm bore. The field will be generated by a superconducting coil system consisting of advanced LTS materials. This basic configuration of HOMER II consists of five concentric coils. For each coil a superconductor of an optimized cross section is used. The two outer coils are connected in series and produce a magnetic field of 12 T at a rated current of 1400 A, which permits the use of NbTi as the superconducting material (Fig. 11). The layers of the NbTi coil system are insulated with axially orientated strips of glassfiber-reinforced epoxy. These strips also create channels for the coolant, namely superfluid helium at

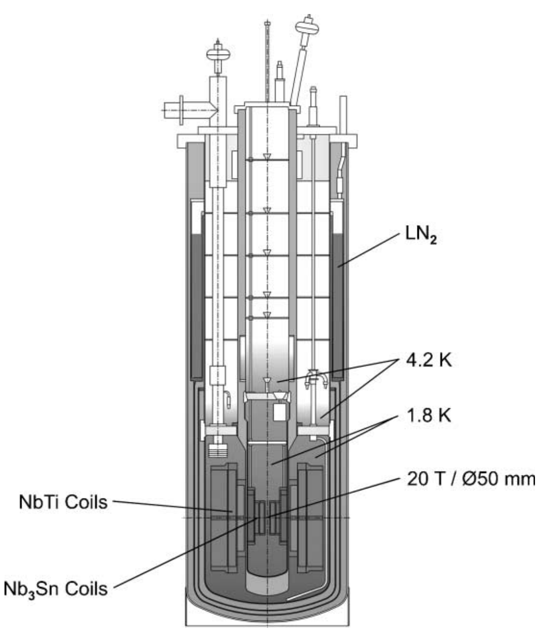


Fig. 10. Schematic drawing of the HOMER I test facility.

Fig. 11. The NbTi magnet section of HOMER II.

1.8 K. The contribution of the three inner coils is 8 T at a rated current of 500 A. $(NbX)_3Sn$ has been chosen as the superconducting material to cope with the total magnetic field of 20 T which occurs in the central bore of 180 mm diameter. In a second step, an insert coil built of Bi-2223 tapes will be added to obtain a total central field of 25 T [46].

MTA I: In cooperation with the industrial partner, Bruker BioSpin GmbH, magnets for NMR spectrometers are being developed. Acceptance tests of the magnet systems for these spectrometers are performed in the facility MTA I. MTA I offers a sufficiently large helium bath volume for magnet systems up to 900 MHz. For tests of 1000 MHz magnet systems and above, the larger facility MTA II is under construction.

3.3. Magnet systems for NMR spectrometers

750 and 800 MHz NMR spectrometer: In the context of a technology transfer project together with Bruker BioSpin GmbH the world's first 750 MHz (17.6 T) [43] and 800 MHz (18.8 T) NMR spectrometers were developed in 1991 and 1995, respectively. Now these magnets are a market product. The core of the NMR spectrometer is its superconducting magnet system, which must be driven in persistent mode to achieve the desired resolution. The requirements are a field drift corresponding to a frequency drift of less than 10 Hz/h and a spatial field homogeneity of approximately 0.2 Hz.

900 MHz NMR spectrometer: In another technology transfer project a 900 MHz (21.1 T) NMR spectrometer was developed together with Bruker BioSpin GmbH. Due to the strong decrease of the critical current of LTS in such high fields, this project was an especially demanding task. To build up a 900 MHz magnet system quaternary $(NbX)_3Sn$ material at reduced temperature has to be used. In 2001 the first Bruker 900 MHz NMR spectrometer was installed at "The Scripps Research Institute" (www.scripps.edu).

1000 MHz NMR spectrometer: Scientists of various disciplines use NMR as a key research tool. To get higher resolution and shorter times to acquire a spectrum, NMR spectrometers with higher magnetic field strengths are required. With this background, a bmb + f project (project supported by the German Federal Ministry for Education and Research) for the development of a 1000 MHz spectrometer has been started together with Bruker BioSpin GmbH and Vacuumschmelze GmbH. 1000 MHz is equivalent to a magnetic field of 23.5 T. This field is close to the upper critical field of technical LTS (see Fig. 8). Therefore these materials cannot be used for the inner coils of a 1000 MHz magnet system. A new class of insert coils built of HTS wires, e.g. Bi-2223 tapes, has to be developed. Although the HTS tapes or wires have sufficiently high upper critical fields, many problems are connected with the use of these materials: their physical properties (e.g. pinning) are highly anisotropic, they must be properly heat treated, and superconducting joints and switches have to be developed. Currently these technical issues are being addressed. An overview of the development of superconducting magnet systems for NMR spectrometers at the ITP is given in Fig. 12.

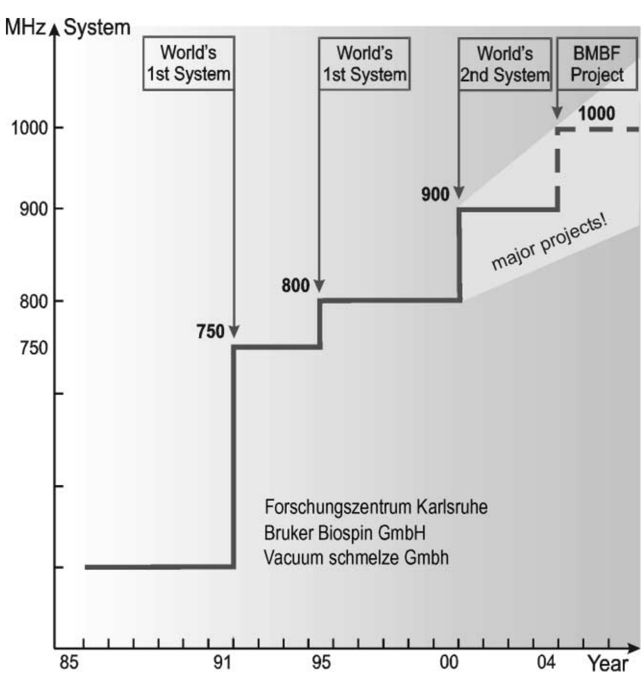


Fig. 12. Development of superconducting magnet systems for NMR spectrometers.

4. Superconductivity for industrial and power engineering applications

Work at ITP has been performed in several promising areas, including magnetic separation and superconducting generators, as well as magnetic energy storage, fault current limiters (FCLs) and power transmission cables.

All applications of superconductivity in the electric power sector have been studied over a period of more than 10 years in the framework of an IEA implementing agreement as Germany's representative together with 13 partner countries worldwide. For every aspect of those applications an overview of the state of the art has been written, which is available to each of the partner countries [47].

4.1. Magnetic separation

The application of magnetic separation to weakly magnetic minerals and ores was the basis for a development programme together with KHD Humboldt Wedag, Cologne. A full size demonstration unit of a novel superconducting rotating drum separator was designed, constructed and successfully operated at the Institute in the 1980s. The core of the demonstrator is a superconducting NbTi magnet operated at 4.5 K [48] (Fig. 13). The major advantages of this concept are the used large open gradient volume, which allows high throughputs of material, simultaneous treatment of a large range of particle sizes from tens of micrometers up to tens of millimeters, easy extraction of the strongly magnetic particles that appear in some processes and could disturb the separation, and the possibility of wet or dry material feed. The industrially built successor plant called DESCOS (drum equipped superconducting ore separator) [49] was the world's first open gradients system in industrial operation. Equipped with a drum of 1.2 m diameter and 1.5 m length it reached more than 100 tonne/h throughput and was successfully operated in a mine in Turkey for the removal of devaluating weakly magnetic particles from the non-magnetic mineral magnesite.

During the past decade our activities on magnetic separation were focused on the support of the Institute for Technical Chemistry Water and Geotechnology, which investigates the applications of magnetic separation for the removal of pollutants from municipal and industrial waste water, and also studies the possible use

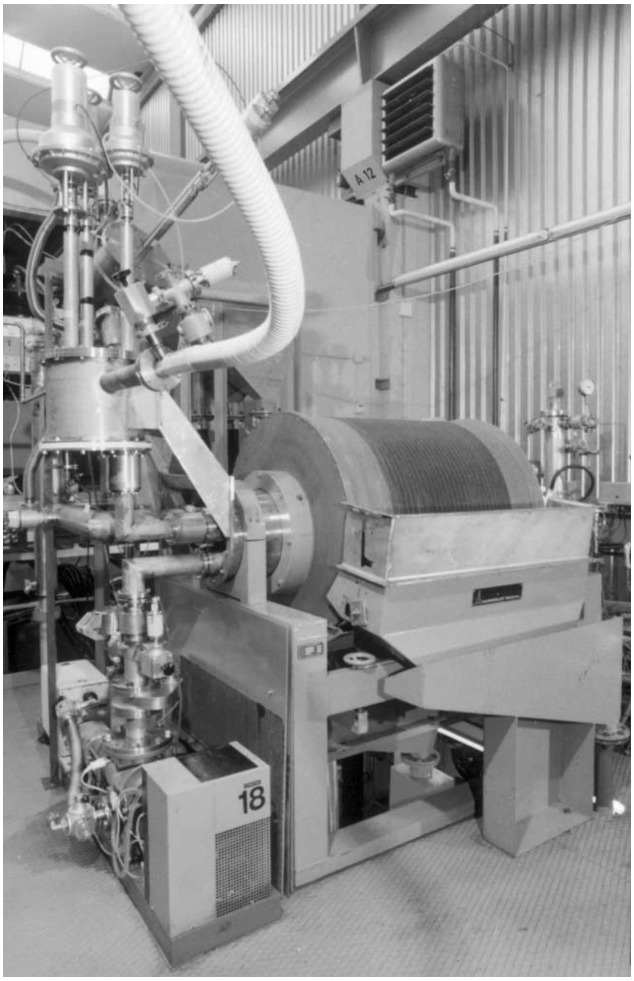


Fig. 13. First superconducting magnetic separator with rotating drum: demonstration unit at the Research Center Karlsruhe.

of magnet technology for the so-called downstream processing in the bioindustry [50,51].

4.2. Electric power engineering

The application of high-current superconductors for electric power technology has been regarded as attractive for a long time. In the 1970s, the Institute was involved in investigating the economics of superconducting power transmission cables and contributions to the rotor cooling of a superconducting generator. Since 1990, the Institute's work has concentrated on magnetic energy storage (SMES) and FCLs together with contributions to power cables. While the SMES magnets are constructed with the low-temperature conductor material NbTi, the FCLs and power transmission cables are already using HTS.

4.2.1. Superconducting generator cooling

In the 1970s, large superconducting power generators with rotating NbTi windings were considered. The LHe

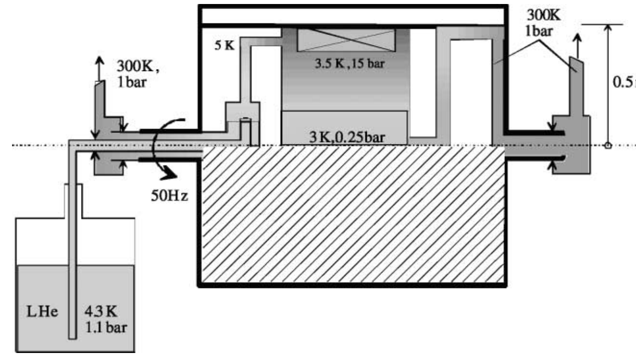


Fig. 14. Operational scheme of a "self pumping" and "self level adjusting" rotating helium cryostat.

coolant is exposed to centrifugal acceleration up to 5000 g. Extensive studies on helium handling [52], heat transfer [53], and helium flow were done. As to the first topic, the high centrifugal force causes an appreciable increase of temperature of the helium flowing from the centerline inlet position to the superconducting winding close to the periphery. The solution investigated experimentally by FZK (Fig. 14) makes use of the centrifugal force to reduce the centerline pressure of the rotating helium pool. This effect over-compensates the temperature rise within the pool [54]. Subatmospheric centerline pressure is obtained by guiding the boil-off gas first to the periphery where it is heated by conduction through the shaft and then back to the centerline exhaust. In both radial ducts the density of the gas will adjust so that the pressure close to the periphery becomes the same, and hence the density of the cold gas has to become nearly the same as the warm exhaust gas. The rotating LHe pool can be replenished from a stationary reservoir connected to normal pressure exhaust lines. The stationary transfer line ending at some radial distance within a co-rotating phase separator makes it possible to control the level of the rotating LHe pool just by a small overpressure within the supply vessel. This simple but very reliable technique has been incorporated in a superconducting generator prototype developed by Siemens [55].

4.2.2. Superconducting magnetic energy storage

The SMES development at the Institute started with a study on the use of SMES for smoothing photovoltaic power generation in those regions where the motion of clouds leads to sags or interruptions of generation. The work performed together with the University of Karlsruhe and the utility EnBW-Badenwerk was funded by the Energy Research Foundation Baden-Wuerttemberg. It was found that economic break-even cannot be reached with LHe cooled SMES, but that the future use of LN_2 for HTS SMES systems would lower the limit down to an attractive 100 kW h/100 kW.

In the early 1990s, the use of so-called Micro-SMES became attractive, when considered for improvement of the quality of power supply [56]. Meanwhile, the SMES-based uninterruptible power supply was introduced into the market with stored energies and delivered power in the megajoules and megawatts range, respectively. A complementary view of power quality requirements has been investigated by ITP with the development of a SMES-based power compensator and active filter, which can avoid those disturbances in the electric network that are produced by industrial loads with fluctuating power demand such as arc furnaces or steel rolling mills [57]. In addition to the compensation of power changes, the SMES compensator can filter the distortions of the sinusoidal shape of the net currents that are produced by AC/DC converters needed by all electronic devices. This system requires a highly dynamic SMES and current converters that can follow the fluctuation and compensate power changes within about 0.3 ms. In collaboration with the University of Karlsruhe and the utility EnBW-Badenwerk and funded by the Energy Research Foundation of Baden-Wuerttemberg, for the first time in Europe a mobile demonstration unit of a SMES compensator with an integrated active filter was developed, providing approximately 100 kW and using a solenoidal magnet with 250 kJ maximum stored energy. Operation was demonstrated successfully at a sawmill in the Black Forest (Fig. 15), which generated a disturbing flicker in the surrounding power consumers. Not only the power variations of the 10 Hz repetitive load but also the distortion of the sinusoidal shape of the currents were compensated and filtered so that the grid saw a 50 Hz sinusoidal current with nearly constant amplitude [57].

In the second and final step of the development program, the magnetic stray field was reduced below the legally permitted heart pace-maker limit by constructing and operating a 10 coil toroidal magnet (Fig. 16). In quench tests this magnet reached 100% of the maximum possible current and 416 kJ stored energy at a magnetic field of 5.73 T [58].

Fig. 15. The first SMES compensator during field tests.

Fig. 16. Ten coil toroidal magnet system for SMES compensator, closing the magnet cooling vessel.

A second SMES development programme of the ITP is conceived to avoid deterioration of power quality. The goal is the generation of high-power pulses in manner compatible with a network. While the technology exists for pulses of microsecond duration, long pulses in the megawatt range with 2 ms duration require new technology. Such pulses are needed for the PS of the radio frequency (RF) power generating Klystrons of accelerators like TESLA at Deutsches Eletronensynchrotron (DESY), where pulsed power up to 10 GW at a repetition rate of 5 10 Hz must be supplied. For this application, a novel power modulator using SMES is being developed at the Institute [59]. A demonstration unit with an output pulse power of 25 MW for operation at DESY is in its final stage of development [60]. The SMES (Figs. 17 and 18) has 237 kJ stored energy at 4 T maximum field, which suggests the use of NbTi. A special requirement for this SMES operation is the very high dB/dt of more than 100 T/s during the power pulse generation. The losses in the superconducting cable are kept low through suitably arranged CuNi barriers between the NbTi filaments within the strands. Intermediate results include the achievement of the nominal current in the magnets and 10 MW pulses using most of the parts of the power electronics. This prototype development may become a model for the power grid connection of plants with high pulse power demand.

4.2.3. Fault current limiter

One of the most attractive applications of superconductivity in the power sector is the use of superconducting FCLs. This novel device limits the current of the electric network in the case of a short circuit to an acceptable value by passively introducing a resistive or inductive impedance when an overcurrent drives the superconductor to the normal conducting state. In the framework of a bmb + f (Federal Ministry for Education and Research) project and together with industrial

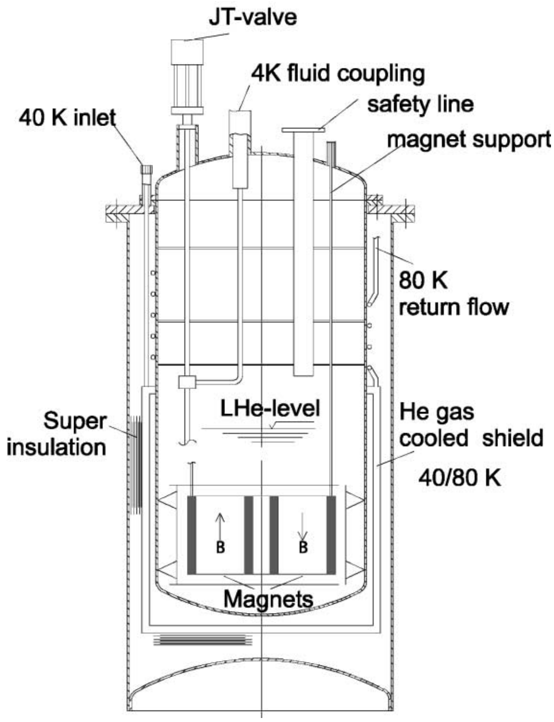


Fig. 17. First SMES power modulator: magnet system with two so lenoids in antiparallel field orientation.

Fig. 18. The 25 MW SMES power modulator ready for installation in the cryostat (coil height: 0.5 m).

partners, the suitability of bulk YBCO and BSCCO for FCLs has been investigated on samples and modules. Measurements of the current voltage characteristics, the

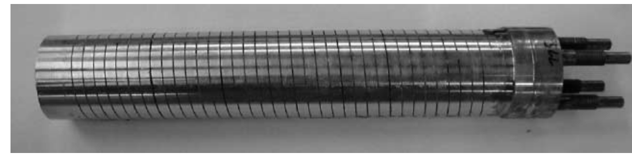


Fig. 19. Bulk bifilar MCP BSCCO2212 coil with integrated metallic shunt (SC length 5.4 m, critical current 800 A at 65 K).

AC losses and the limiting behaviour in case of a short circuit have demonstrated the applicability of this concept [61]. In tests on modules of BSCCO non-inductive spirals (Fig. 19) with an integrated high-resistive metallic shunt, a power per module of about 100 kV A was achieved at an operating temperature of 65 K (Fig. 20) [62]. These modules will be used for the network demonstration unit of 15 MV A/10 kV (Fig. 21), which is under construction. The transfer of the technology from the medium voltage level to 110 kV has started and the

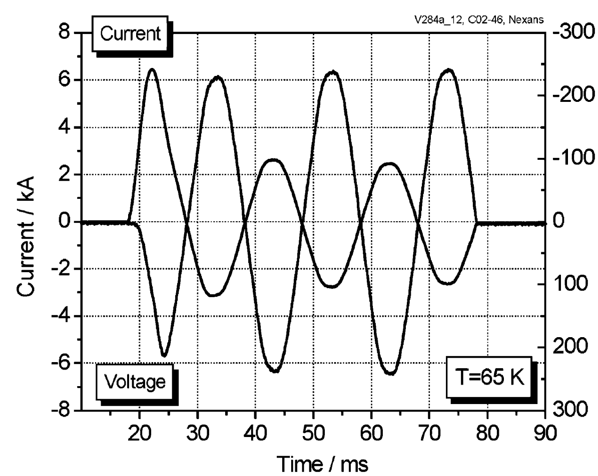


Fig. 20. Demonstration of the current limitation capability of a BSCCO bifilar coil module.

Fig. 21. Artist's view of the 15 MV A class network demonstrator of the FCL under development (courtesy ACCEL).

possibility of extending the activities to the high-voltage level is being explored.

4.2.4. Superconductor power transmission cables

In the 1970s a study on the economics of LTS for power transmission cables was performed with the result that operation was not possible or economical in central Europe [63]. This discussion was reconsidered as an application of HTS after their discovery in 1987. Economic operation looks promising in the cable routes of large cities when replacing the oil cables by HTS cables that increase the transferred power [64]. In the framework of a project of the bmb + f with Siemens as major contractor using suitable HTS conductor (see Section 5.1.3), electrical and thermal insulation (see Sections 5.3 and 6.6) at cryogenic temperature were investigated. A test facility was constructed (200 kV, DC, AC, pulse voltage) to select a suitable electric insulation design and material (Fig. 22) [65].

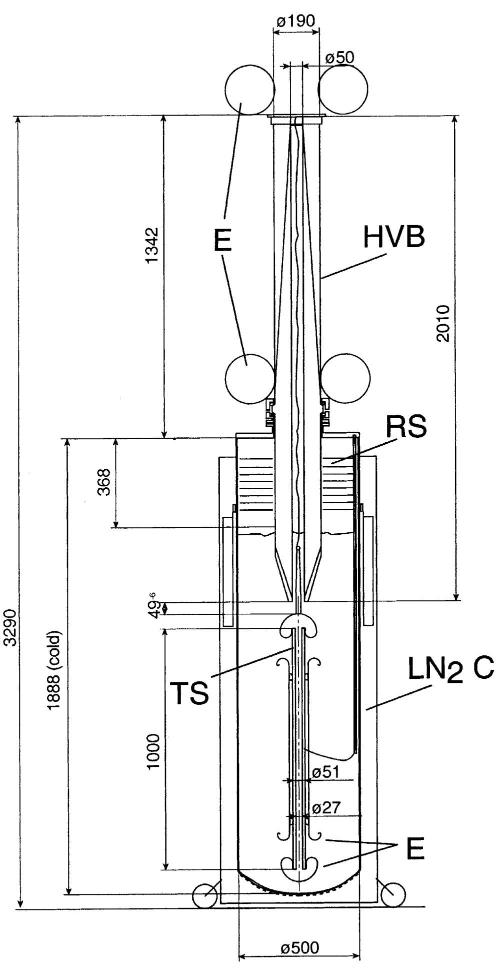


Fig. 22. Facility for testing the insulation of HTS energy transfer cables (HAIhKE), HVB: high voltage bushing; E: control electrodes; LN_2C: liquid nitrogen cryostat; RS: radiation shields; TS: cable test sample.

5. Basic engineering science, research and development

For on-going projects, an accompanying basic engineering research is indispensable for creating a database for the design work and solving arising problems during construction in a reasonable time.

5.1. Development of low-temperature and high-temperature superconductors for application

The R&D of superconducting materials in the ITP was always strongly focused on conductors for technical applications and motivated by the need to increase transport currents towards higher fields generated by superconducting coils for fusion research, NMR magnets, and for energy related components such as transformers, energy storage coils (SMES) and motors. For AC driven devices or pulse operated coils, specific developments in low AC loss conductors were requested and investigations on this topic were started. The activities cover a wide range from basic material preparation and characterization to concepts for technical conductors, the investigation of preparation routes and the investigation of the superconducting properties as a function of temperature, background magnetic field and mechanical strain.

In the years 1979 1980, intensive work began on the investigation of the LTS A15 systems Nb_3Sn and Nb_3Al, as the most important materials for generating higher fields than achievable with NbTi. The main challenge was to improve the critical current densities and upper critical fields, by using improved materials. Most of the work was performed on the basis of technology transfer contracts with industry. In the years 1983 1990 work on the next generation of high-field materials, the Chevrel phases ($Pb_{1-x}Sn_xMo_6S_8$) was performed, motivated by the observed extremely high B_{c2} of up to 50 60 T at 4.2 K.

With the discovery of HTS in 1986, LN_2 cooling became a possibility few years later and the extremely promising superconducting properties, high-current densities and extreme high critical fields at LHe (>100 T). This led to a nearly complete switch of R&D activities to this new material class. The work focused first on BSCCO tapes and YBCO bulk materials. Since 1998, YBCO as a coated conductor on metallic substrate tapes was investigated in the framework of a national collaboration with universities and industries. Very recently, the discovery of superconductivity in MgB_2 with a T_C of 39 K initiated the exploration of the potential of this new compound, leading to the development of MgB_2 wires and tapes.

In the following sections, the achieved highlights and milestones for the specific materials are reviewed.

5.1.1. A15 phase superconductors

In the 1970s, a lot of fundamental research on A15 bulk, wire and thin film samples showed that alloying and more sophisticated preparation methods could improve pinning and high-field properties. For the most interesting system, Nb_3Sn, ternary substitutional alloying with Ti, Ta, Zn, Ga, etc. were investigated on multifilamentary wires, improving the material with respect to several properties [66]. The ternary additions suppressed the spontaneous structural phase transformation to the tetragonal phase and improved the Sn content towards stoichiometry via faster diffusion paths [67]. The microstructure was improved towards smaller grains, resulting in enhanced flux pinning. In ternary Nb_3Sn wires, the current densities increased significantly and this new technique rapidly became the industrial standard for wires used in high-field applications. The B_{c2} values were improved by about 3 5 T to values close to 28 30 T. Supporting a high Sn content for the phase formation, internal tin diffusion techniques were applied (Fig. 23) [68]. Since the efforts to achieve small grains were limited by grain growth during annealing, innovative methods such as the introduction of artificial pinning centers and powder-metallurgical approaches were investigated for the wire preparation with good success but limited applicability for technical conductor lengths of several km [69]. These investigations demonstrated the potential of the material but failed to generate an industrial application.

In parallel with the Nb_3Sn development, Nb_3Al became of high technical interest due to the potential for a significantly higher B_{c2} of approximately 35 T. The meta-stability of the stoichiometric compound at RT required completely new preparation schemes such as microalloying and powder-metallurgical approaches or extremely fast quench methods from temperatures of about 1900 °C. Although much improved wires could be prepared by this method, the limited deformability of the materials for technical conductor lengths hindered the rapid breakthrough of these approaches to industrial processes [70].

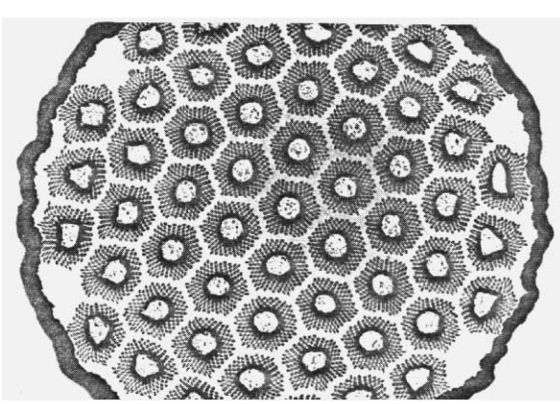


Fig. 23. Internal Sn diffusion Nb_3Sn wire, 55 cores 7260 filaments [68].

During this time, pioneering work was done on experimental investigation of stress and strain induced effects on superconducting wires [71]. This includes the construction of axial tensile strain rigs for background fields up to 20 T (HMFL, Grenoble). From those investigations conductor reinforcements to improve the mechanical properties, such as steel reinforcements were developed. Experimental methods were extended to larger assembled conductors, as subsize conductors for toroidal field coils of fusion reactors, with forces up to 100 kN and 10 kA current (see Fig. 4a and b). For coils, transverse stresses are the most important and new kinds of strain rigs allowed the application of transverse stresses to the conductors [72]. Such investigations were performed first on Nb_3Sn wires, then Chevrel phase wires [73] and later on HTS tapes [74] with continually improving strain rigs.

A theoretical and physical understanding of the stress and strain effects was generated by investigations of the strain tensors in standard and reinforced Nb_3Sn wires by means of neutron diffraction studies of the crystal structures at different temperatures [75]. 3D-modeling of the stress and strain states in Chevrel phase wires demonstrated the importance of the 3D-nature of the residual stress state in the superconducting filaments [76].

5.1.2. Chevrel phases

The development of Chevrel phase wires required a new fabrication method, including precursor pre-reaction using HIP (hot isostatic pressing) techniques [77], and the powder-in-tube (PIT) technique. This was a new challenge for the deformation technique and conductor heat treatments. Using a very complicated four component conductor with a steel/Cu/Nb (or Ta)-sheath, mechanically stable monofilamentary wires were developed that carried high-current densities of up to 2×10^4 A/cm^2 at 20 T and a temperature of 4.2 K, which is the best value for this material. The limitation of this technique to monofilamentary wires, the failure of further current improvement and rapid success with the new HTS conductors destroyed the chance of further progress in these materials or in possible technical application. The activities were stopped as a consequence in 1990.

5.1.3. BSCCO(2 2 2 3) tapes

The discovery of the HTS conductor BSCCO(2 2 2 3) with a T_C of 110 K opened the possibility of LN_2 bath cooling. The two-dimensionality of superconductivity in this compound required the creation of phase texture which can be achieved only in a tape geometry. A new preparation scheme, the PIT process, and sophisticated rolling processes were now necessary (Fig. 24). The chemical reactivity of BSCCO and some oxygen ex-

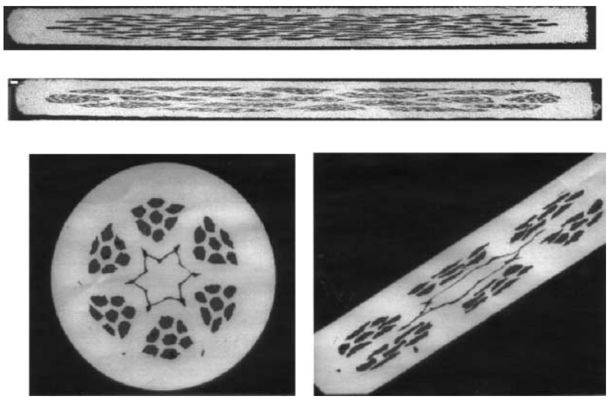


Fig. 24. Cross sections of BSCCO conductors: 85 filament standard tape (top), 703 filament tape (middle) and ring bundle barrier (RBB) tape for low AC losses (central resistive barrier).

change during reaction required the use of an Ag sheath, which had the disadvantage of poor mechanical performance that was not sufficient for most applications. The phase formation from the multiphase precursors required complex and very accurate heat treatments. One first milestone was therefore the first introduction of AgMg dispersion hardened sheaths in BSCCO(2 2 2 3) conductors, which also became the industrial standard (Fig. 25) [78]. AgMg/AgAu sheathed conductors were developed for use in current leads [79]. AC applications in power cables, transformers and motors soon became of dominant interest for applications. Since in standard conductors an effective coupling of the filament due to the very good conducting Ag sheath leads to high AC losses, an innovative method of resistive barrier layers in the sheath between the filaments was introduced [80]. The results were very promising and the measured decoupling of the filaments corresponded to an AC loss reduction of 40% or more at 50 Hz AC current. The

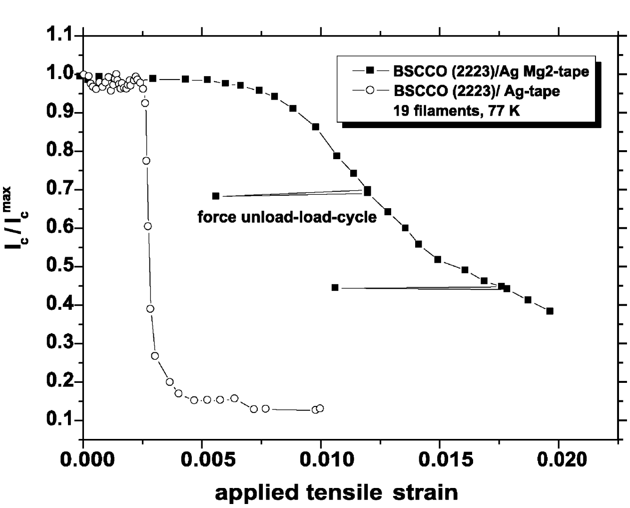


Fig. 25. Critical current versus axially applied strain for 19 filament BSCCO tapes with Ag sheath and $AgMg_2$ dispersion hardened sheath.

development of these new conductors is continuing, since an enhancement of the thermodynamically limited current densities is absolutely necessary for application. Many AC applications require high-current conductors with low AC losses. A new tape geometry with a Rutherford cable-like structure was developed and allowed very effective filament twists and excellent decoupling of the filaments [81]. Methods to increase the suppressed current carrying capability in these innovative concepts are also under investigation. Since 1992, the R&D activities for BSCCO(2 2 2 3) has been included in European projects (BriteEUram3 and 4, and 5th Frame Program of the European Union) with industrial collaborations.

5.1.4. *YBCO coated conductors*

Since 1998, a coordinated effort has existed in Germany to develop YBCO coated conductors on the basis of cube textured NiCr alloys. The main contribution of the ITP to this research is to improve the texture quality of the substrate tapes, to avoid single wrongly oriented grains and to define the process parameters for reproducible preparation of long substrate tapes. For this purpose, short time annealing techniques were applied and differential scanning calorimetry investigations were used to quantify the thermodynamics of the recrystallisation [82]. The deformation method, rolling texture and recrystallisation parameters are of the most importance for an improved texture quality and are the main goal of the investigations. The microstructure, individual grain orientations and their statistical distribution, i.e. texture, were analyzed by the SEM-based electron back scatter diffraction (EBSD) technique, which is the most advanced analytical tool for this purpose. For NiCr alloys, state of the art textures with less than 5° out-of-plane misorientation were achieved. Thermodynamical studies of the kinetics of the recrystallisation process allowed a fast adjustment of the heat treatment conditions of new alloys.

5.1.5. *MgB_2*

The discovery of superconductivity in this compound in January 2001 initiated worldwide efforts in investigating thin films, wires, tapes and bulk materials. This material is of technical interest due to a T_C of 39 K and very high critical current densities of up to about 10^7 A/cm^2 at 4.2 K in self-field. Methods used to fabricate Chevrel phase wires could successfully be applied and adapted for wire and tape concepts, and mechanically reinforced monofilamentary conductors were developed and characterized (Fig. 26) [83]. Although critical transport current densities of above 10^5 A/cm^2 were achieved at 4.2 K in self-field, being the highest transport currents reported for these wires so far the potential for superconducting transport currents is 100 times higher as demonstrated in textured thin films. Sample

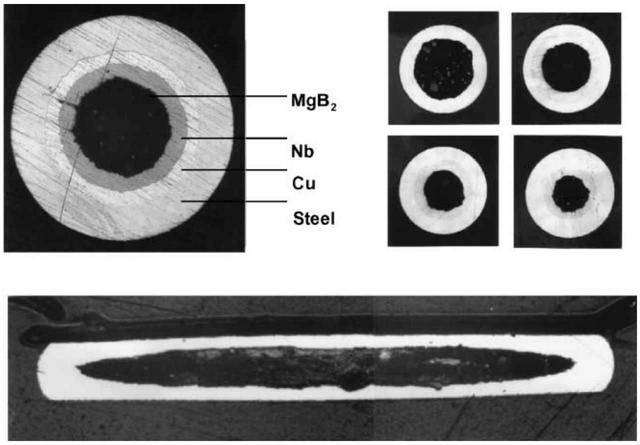


Fig. 26. MgB_2 conductors: MgB_2/Nb/Cu/steel wire (top left), MgB_2/Fe/steel wires with different steel contents (top right), diameter 1 mm, MgB_2/Fe tape ($\approx 3 \times 0.35$ mm).

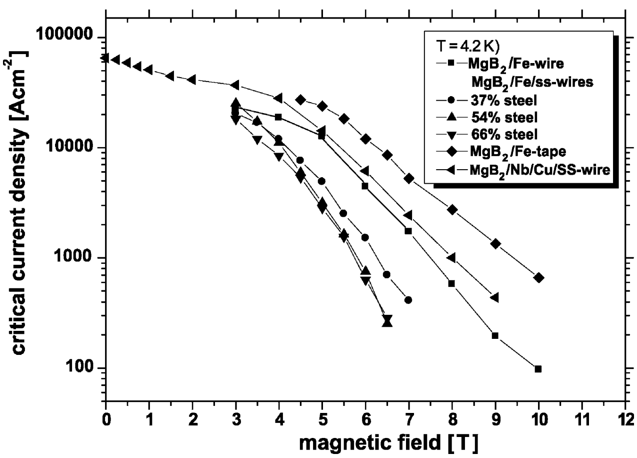


Fig. 27. Transport critical current densities of different MgB_2 con ductors: wires and tape with different sheath composites applying pre reacted MgB_2 precursor.

densification, phase homogeneity and purity are limiting factors and cause spontaneous quenches at current values well below the values obtained from magnetic measurements (Fig. 27) [84]. The superconducting properties show a significant stress and strain sensitivity, which can lead to irreversible partial damage of the conductor [85]. This is of most importance for mechanically reinforced wires [86]. MgB_2 may become very interesting for niche market applications in persistent mode magnetic resonance imaging magnets. The general behaviour resembles more LTS conductors than HTS conductors but much R&D are necessary to improve the phase homogeneity and purity and to develop multifilamentary wires or tapes with sufficient thermal stabilization.

5.1.6. Basic physical properties

The development of superconducting materials is always accompanied by investigations of their physical properties. For the low-T_C superconductors, structural instabilities are of particular interest. They manifest themselves in an enhanced electron phonon coupling, but may also initiate a transition to a crystal structure with reduced superconducting properties, when the material is simply cooled down or exposed to mechanical stress, e.g. by Lorentz forces. The structural transitions have been thoroughly studied through changes of electric, magnetic, and mechanical properties as well as with microscopic and spectroscopic means.

In A15 materials, X-ray investigations under high pressure revealed the sensitivity of the martensitic cubic-tetragonal transformation to changes of the lattice constants [87]. While Nb_3Sn can be stabilized in the cubic structure by substitutional alloying as described in Section 5.1.1, Nb_3Ge could only be obtained in a metastable state by thin film deposition, thus achieving a transition temperature above the important 20 K limit [88]. For cubic (bcc) NbTi, the lattice instability was traced back to the microscopic origin. It has been shown that the development of elastic strain fields finally stabilizes the structure, known as the training effect. General insight into the plastic instabilities of structural materials for magnets at low temperatures emerged from tensile tests with fcc materials such as copper and austenitic stainless steel. It could be demonstrated that a load drop, as precursor to failure, stems from dislocation motion controlled by viscous and thermally activated mechanisms [89].

The attempt to develop a (carbon fiber, NbN)-composite conductor combining high tensile strength with excellent superconducting properties was successful and patented, but the initial interest in this new conductor decreased significantly after the discovery of HTS [90].

The early availability of high-quality single crystals of the high-T_C (RE)$Ba_2Cu_3O_x$ family and the consequent chemical and structural characterization by high-resolution SEM/EDX analysis and neutron diffraction facilitated a successful investigation of thermodynamic properties. Calorimetric and dilatometric investigations under high pressure on differently doped crystals reveal the influence of oxygen content and ordering on the charge carrier density which determines T_C in a universal way [91,92].

For the understanding of the field and temperature dependence of the critical current density, $j_C(B,T)$, of superconducting materials, DC and AC magnetization measurements have been performed and analyzed in the framework of flux pinning models. Whereas in the case of strong pinning centers, e.g. for NbTi, the elementary pinning forces at structural defects can add linearly, in materials with weak pinning centers, commonly existing in A15 materials, the elastic energy of the flux matter must be taken into account. This leads to a collective flux-line pinning which causes an increase of j_C at high fields. This "peak effect" has been studied in-depth on single-crystalline V_3Si as a representative of the A15 materials [93]. The individual structure of pinning centers has been visualized with high-resolution electron microscopy [94].

For the high-T_C superconductors, the thermal energy leading to thermally activated flux creep can no longer be neglected. The interplay between the pinning energy, the vortex interaction energy, and the thermal energy now causes a variety of phases of the flux matter in the B T phase diagram. Against this background, in particular the influence of the oxygen content on $j_C(B, T)$ has been investigated in great detail. Starting from almost defect-free single-crystalline $YBa_2Cu_3O_x$ and $NdBa_2Cu_3O_x$ at $x = 7$, the importance of oxygen-vacancy clusters for flux-line pinning was demonstrated and it was shown that high critical currents and maximum critical temperatures do not come into conflict in cuprates [95].

In addition to DC magnetometry, AC methods were successfully used for the investigation of the flux dynamic in thin films [96]. Hall-sensor magnetometry proved especially suitable for the contactless test of the critical current homogeneity of long BSCCO(2 2 2 3) tape conductors (Fig. 28).

It has been demonstrated that this inductive method detects the same current system as a resistive one [97]. A prototype "Tacho" (Tape Current Homogenity) has been built and patented.

In a similar way, basic investigations of texture by EBSD became of fundamental importance for the development of YBCO coated conductors (see Section 5.1.4).

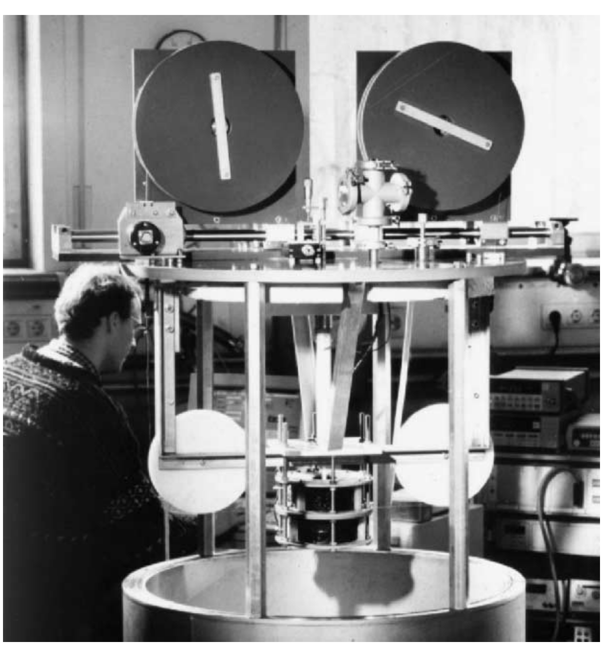


Fig. 28. Equipment for continuous homogeneity test of critical currents for long length HTS, such as multifilamentary BSCCO(2 2 2 3)/Ag tapes.

5.2. Material properties at cryogenic temperatures

A sound structural materials database is essential for the engineering design and construction of large superconducting magnet systems that are capable of withstanding forces of several hundreds of MN. At the end of the sixties, a limited structural engineering database was available from the activities of liquid natural gas container manufacturing and large hydrogen bubble chambers design for high-energy particle physics [98]. For fusion technology, the design of large magnets requires basic engineering data of the base and weld materials at low temperatures. Therefore, the adaptation and the development of measurement techniques for material characterization at 4 K was an important part of the work.

5.2.1. Equipment for cryogenic material tests

Within the framework of the fusion magnet tasks, several low-temperature mechanical test facilities were designed, completed and operated (Table 3).

The operation of mechanical tests at cryogenic temperatures requires reliable, on-site displacement transducers. Based on strain gauge and current extensometer technology, design and development of suitable displacement transducers were initiated for a variety of specimen types [100]. Within the last two decades several types of extensometers were developed at ITP by continuous improvements made for different mechanical test programs. The extensometers produced to date are highly reliable and are used at several institutions around the world, ranging from measurement tasks for fragile BSCCO high-temperature superconducting tapes of the size 0.2 mm $\times$ 4 mm (extensometer mass less than 2 g) up to large size tensile specimens of 22 mm $\varnothing$ [101]. In addition, these extensometers are able to determine the strain of the specimen under test up to 60% strain. The accuracy of these high sensitivity (resolution <0.2 μm) extensometers is below 1 μm at 4 K.

5.2.2. Measurement of tensile properties

The determination of mechanical tensile data is well defined by several standards [102 104]. However, they are not directly applicable at 4 K being limited to RT and to 77 K. The new ISO standards committee [105], of which ITP is a national committee member, will guide the tensile tests in near future for 4 K tests. However, these standards usually do not define the Young's modulus determination at zero offset. This engineering quantity is important for the finite element method of structural mechanical analysis and for the development of new superconducting materials. For Young's modulus determination to date, only the ASTM E 111

Table 3
Mechanical test facilities at the cryogenic material testing laboratory

Machine details	200 kN Zwick machine	630 kN Schenk machine	25 kN MTS machine (Fig. 29)
Installation year and operation	1978 2000	2000 to date	1987 to date [99]
Load capacity	200 kN	630 kN	±25 kN
Type	Screw driven	Servo hydraulic	Servo hydraulic
Operation and environment	LHe or LN2	LHe or LN2	7 300 K He gas
Cryostat type and diameter	Bath 400 mm ∅	Bath 400 mm ∅	He flow 180 mm ∅
Tensile specimens	4 12 mm ∅	422 mm ∅	0.24 mm ∅
K_{IC} specimens	Compact tension 6 24 mm	Compact tension 6 40 mm	Compact tension 2 6 mm
FCGR specimens			Compact tension 2 6 mm
JETT specimens	6 mm ∅		6 mm ∅
Multispecimen rig	Four specimens tensile or fracture	Four specimens tensile or fracture	Four specimens JETT
Kind of testing	Static	Static and dynamic	Static and dynamic

FCGR: fatigue crack grow rate; JETT: *J* evaluation on tensile test, Section 5.2.3.

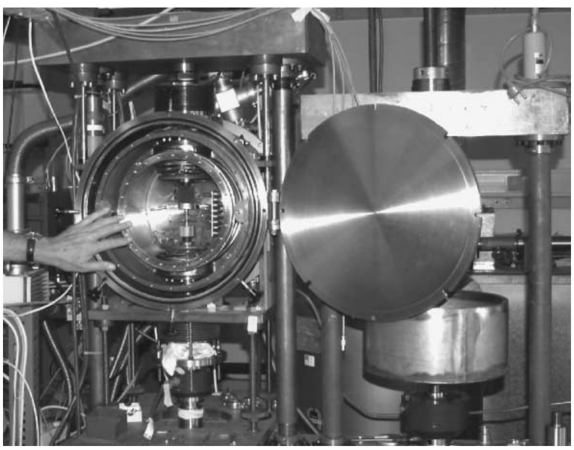


Fig. 29. The test chamber of the 25 kN MTS machine cooled by a helium flow cryostat for generating variable temperatures.

standard [106] is applicable. Although this standard was reapproved in 1988, it is not recommended to use the stress strain curve's initial tangent modulus (slope of the stress strain curve at the origin) because of the difficulties of establishing the zero offset line experimentally. The standard recommends, instead, the use of the double extensometer system, which was considered at ITP since the mid-1980s, when ITP successfully developed a measuring technique using two independent extensometers attached to the tensile specimen in 180° position, working at 4 K. Using the specific data acquisition (18 bit resolution) and evaluation software, to date, the system is capable to analyze the engineering parameters (Young's modulus, yield and tensile strengths, and elongation) with a ±3% accuracy for the Young's modulus.

5.2.3. Measurement of fracture toughness properties

Along the high yield strength, an additional stringent requirement for materials used as structural parts for heavy loaded components is to have a reasonable high fracture toughness. Beginning with the EURATOM LCT coil development, ITP actively worked out a technique to determine the fracture toughness of the baseline 316LN 50 mm thick case material (base and weld). The 200 kN test facility was ready in 1981 to measure the fracture toughness K_{IC} of the case material at 4 K using the multispecimen *J*-integral test method according to ASTM E 813-81 [107]. Since then, the method has become a standard test technique at ITP and during the eighties a variety of different structural materials was successfully tested at 4 K [108]. Fig. 30 shows the established database for several structural materials. The diagram addresses the performance of the material at 4 K and gives valuable information about the strength and toughness relation of the particular material for structural applications.

The need for fracture toughness data for ITER full size superconductor conduits (jacket material) raised the question of seeking a test technique with small size specimens machined from jacket structures. In close

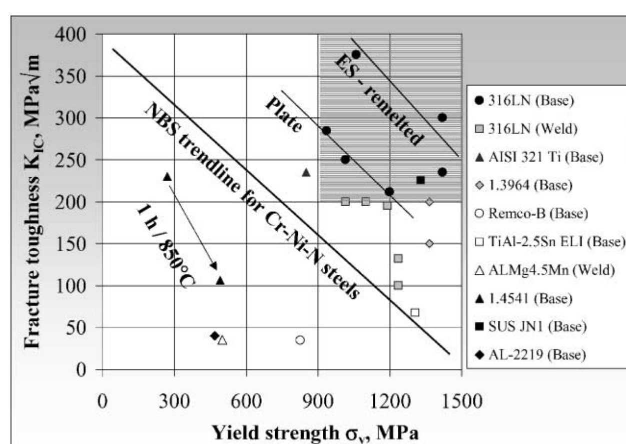


Fig. 30. Fracture toughness versus yield strength diagram. Data of different structural materials were established between 1980 and 1990 to be used in design of superconducting magnets. The shaded area represents the so called JAERI (Japan Atomic Energy Research In stitution) box, recommended for materials selection of heavy loaded structures at 4 K [109,110].

collaboration with NIFS (Gifu, Japan) a novel test method called *J*-evaluation on tensile test (JETT) was successfully developed, which was able to measure the fracture toughness of small size (6 mm ∅, 60 mm long) specimens at cryogenic temperatures [111 113]. A recently conducted worldwide round-robin test showed the potential of this current test technique.

5.2.4. Measurement of cyclic loading properties

The requirement in fusion technology for cyclic material database has necessitated the collection of additional cryogenic fatigue crack growth rate (FCGR) data. The dynamic mechanical behaviour of that used LCT case material, Type 316LN was measured at 4 K with large compact tension specimens of 24 mm thickness. In the early stage, these measurements were based on an estimation of crack lengths during the necessary fatigue pre-cracking of fracture toughness tests [114]. The recent comparison of these data with measurements conducted using the new cryogenic mechanical test facility (MTS 25 kN servo hydraulic machine) showed the excellent agreement of both types of measurements, as shown in Fig. 31. The FCGR test is now standardized with respect to the test procedure and the type of specimen. In Fig. 31 a data set of current test results is given concerning ITER cryogenic structural materials. In addition, the fatigue life data of the structural materials were established with standard small size specimens up to 1 million cycles at 7 K. These important data give additional information about the real structural performance of a cyclic loaded member in its non-artificially cracked state, when compared to FCGR tests. The verification of these fatigue life cyclic test results with full size structures will be the next step of the material test program. Preliminary tests at 4 K with full size jacket structures of the ITER central solenoid superconductor should verify that the presently installed large 630 kN capacity servo hydraulic machine is capable of carrying out tests under four-point bending mode for load ranges of $\Delta P = 400$ kN with 2 Hz frequency without major problems.

5.2.5. Component tests

Besides the determination of basic engineering material properties, testing of small-scale components, which represent a model of a real structure are essential during the development phase of magnets. Typical tasks within this framework are as follows:

- Friction coefficient of structures joined with pre-stressed bolting [115].
- Shear strength of conductor to conductor bonds by insulating composite materials [115].
- Sliding properties of the ITER TFMC conductor at the joint region [115].
- Oxygen partial pressure and its impact during aging of jackets produced by superalloy Incoloy 908 material [115].

The cryogenic material laboratory has made essential contributions to the development of suitable testing techniques at low temperatures and the engineering database of structural materials for fusion magnets. The laboratory's expertise and equipment is presently unique in the world.

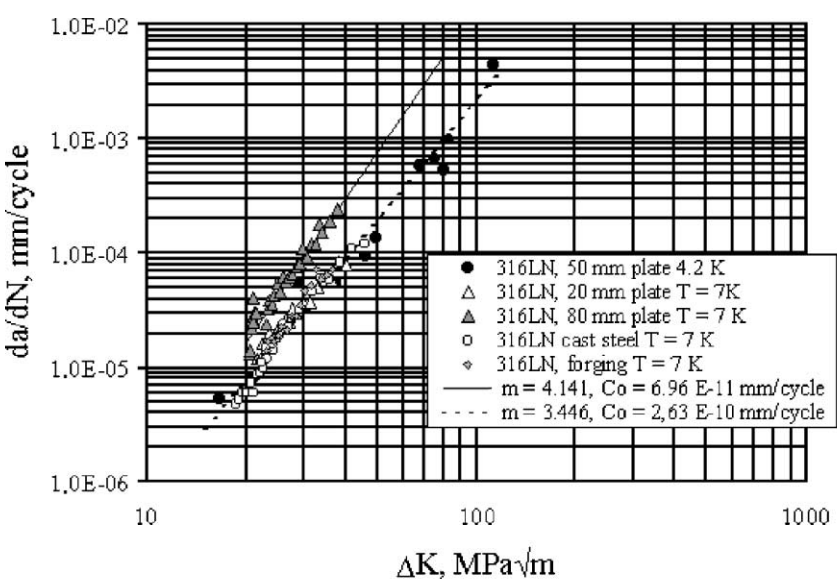


Fig. 31. FCGR test results with Type 316LN structural materials. Black circles indicate the LCT case measurements at 4.2 K [114]. The 80 mm thick plate, cast steel, and forged 316LN represent the currently candidate structural materials for ITER.

5.3. *High-voltage engineering*

The mastering of electrical insulation technique is an indispensable requirement for electrical machinery. The high-magnetic energies stored in fusion magnet systems require high voltages for charging and removal of magnetic energy (see Section 2.2.3). Voltage levels up to 20 kV in superconducting magnet technology have been mastered. Therefore, a cryogenic high-voltage laboratory with suitable equipment has been necessary for making insulation tests on magnets and for the development of components used in operation at low temperature (Fig. 32) (see Section 2.2.6). The high-voltage equipment includes voltage sources up to 200 kV (AC, DC and pulse), measuring equipment (voltage dividers, partial discharge measuring equipment, tan δ measuring bridge), and cryostats with bushings for the voltage levels required.

Since the magnets are exposed to switching procedures during the fast safety discharges, the response of the electrical network representing the magnet winding on transient voltages has to be considered [116].

For the development of superconducting power transmission cables, techniques for handling voltages between 50 and 500 kV have to be mastered (see Section 4.2.4).

Fig. 32. The cryogenic high voltage laboratory with the high voltage power supply and measuring equipment on the right hand side, on the left hand side a part of the test facility HAIhKE (Fig. 22) can be seen, the whole arrangement is enclosed in a Faraday cage.

6. **Cryogenic supply, development and research**

Almost all project requirements of the Institute so far have necessitated the use of helium cryogenics. The RF superconductivity projects in the seventies even needed 1.8 K refrigeration. For this reason, two 1.8 K/300 W refrigerators were constructed and delivered by Linde and Messer Griesheim. Both refrigerators are capable of liquefaction and refrigerator mode operation at 4.4 K, as well. A 2 kW refrigerator was added in the 1990s for the extension of the TOSKA facility.

Every experimental area has its special requirements for the helium supply, the cold helium feedback to the refrigerator or to the recovery system. The helium management has to be adapted to the actual experiment and handled by appropriate measuring and control systems. Special accompanying research and development work is necessary for the corresponding cryostats and cooling circuits of the actual experiments.

6.1. *Refrigeration and liquefaction plants*

The unique, powerful, and flexible "300 W/1.8 K" plants of Linde and Messer Griesheim were used successfully in a large number of RF and high-current superconductivity projects. The plants, equipped with dry piston compressors and upstream oil-free roots blowers for operation at 1.8 K, were mainly used for combined operation with up to three parallel loads plus liquefaction into the LHe storage tanks [117]. The Messer Griesheim plant was decommissioned in 1995 after nearly 40,000 h of operation and donated for further use to the Institute for Plasma Physics of the Academia Sinica at Hefei, China. The more compact, more powerful Linde plant commissioned in 1971, which has meanwhile been upgraded with respect to its measurement and control technology (113,000 h of operation by 2001), is still much in demand as a highly reliable refrigeration plant and as a liquefaction plant.

To increase the He I refrigeration capacity for the operation of fusion magnets that are forced-flow-cooled by supercritical helium, another Linde refrigeration plant was commissioned in 1993 with an equivalent 4.4 K refrigeration capacity of 2 kW as continuous performance ($\approx$2.5 kW discontinuously by LHe consumption from an integrated 10,000 l tank) [118]. This refrigerator is equipped with oil injected screw compressors and turbines with dynamic gas bearings. Up to now, it has been used for 26,000 h of reliable operation and, especially, for cold He supply of the TOSKA facility. The plant can run 10 fully automatic operation modes comprising 3.3 K refrigeration, 4.4 K refrigeration, liquefaction and combinations of each. During the cryogenic supply for the TOSKA facility the plant worked very successfully, mostly over many weeks, at operating temperatures between 3.3 and 4.4 K (Fig. 33).

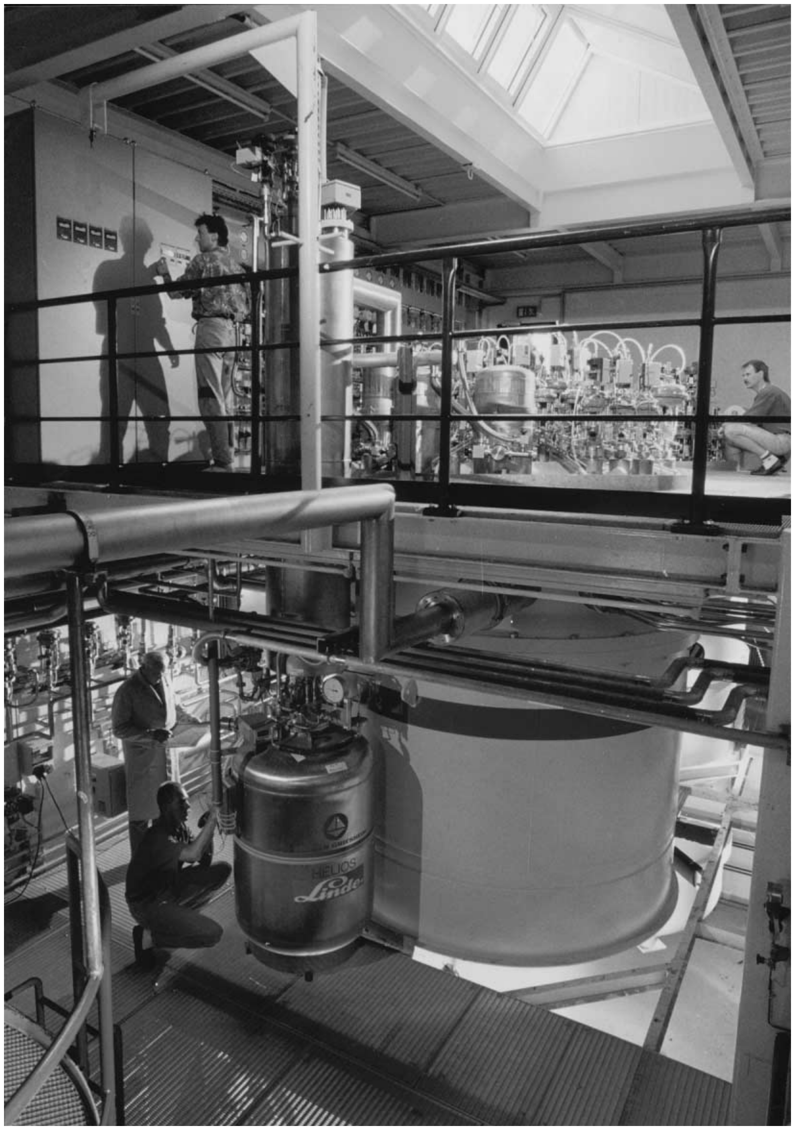


Fig. 33. The 2 kW/4.4 K refrigerator hall with the valve and cold box.

6.2. He supply and recovery system

The two present refrigerator/liquefier facilities are parts of a powerful, highly flexible helium supply and recovery system. This system meets the special requirements of a large laboratory with a large number of loads, continuously changing refrigeration requirements in two experimental halls, and the additional LHe requirement in small laboratories of ITP and other institutes of FZK. Table 4 presents an overview of the current scope and performance of the state-of-the-art FZK interconnected helium facility system.

6.3. Cooling circuits and test facilities

The first requirements arose from high-energy physics in the 1970s. For economic reasons, closed refrigerator circuits were needed with the "300 W" plants in which superconducting cavities had to be cooled in saturated superfluid baths, and superconducting magnets in normal-fluid He I baths. The refrigeration capacities at 1.8 and 4.4 K of the circuits added up to approximately 100 300 W.

A large number of the superconducting systems and cryogenic circuits developed and tested at the Institute were designed for commercial applications and locations [1].

From the 1980s onward, the work concentrated on cooling circuits for high-capacity fusion and high-field magnets which were designed, built and operated at the Institute. This changed the requirements to be met in refrigeration, cryostat and cooling circuit techniques. From that time the large-volume, high-capacity forced-flow-cooled fusion magnets have been cooled in

Table 4
ITP He supply and recovery system

Upgraded Linde 300 W/1.8 K refrigeration plant (380 W at 1.8 K; 600 W at 4.4 K; 5 g/s LHe)
Linde 2 kW He I refrigeration plant (2 kW/4.4 K; 700 W/3.3 K; 1000 W/80 K; 9 and 22 g/s LHe, respectively)
L' Air Liquide purifier plant (14 g/s at 200 bar)
He recovery system (total 30 g/s; 30 and 200 bar respectively)
He storage facility (16,000 scm GHe; 3000 kg/24,000 l LHe)
Two LHe filling stations (current LHe output 200,000 l/a)
Three He transfer line systems with an overall length of 350 m, connected to 8 experimental stations
Six refrigerator circuits with the test facilities: TOSKA, STAR, TIMO, HOMER I, HOMER II and MTA I
Quench gas recovery system ≈200 m long, with 4500 kg of basalt stone pre heater and a gas balloon of 200 m^3
LN_2 supply system with a 30,000 l tank and ≈200 m of distributing piping

stationary mode within autonomous secondary circuits. Separate circuits are used for cryogeneration and supply (primary circuit) and for magnet cooling (secondary circuit). The thermal coupling point of the two circuits is a LHe HEX bath cryostat, in which the cold pumps are also installed for circulating the helium through the cooling channels of the magnet (Fig. 34). The LHe bath and the superconducting magnet are located in different cryostats (HEX bath cryostat and magnet dewar). A prototype facility employing this concept was the HELITEX facility designed and used for cryogenic investigations in forced-flow-cooling of superconducting magnets. The same principle of a magnet cooling circuit is being used in the larger, more powerful TOSKA facility.

Different cooling circuits and experimental facilities were developed and built for development, testing, and operation of high-field magnets. Here the superconducting systems made up of concentric solenoids are cooled in subcooled superfluid baths for reliable stabilization. As the HOMER I and HOMER II experimental facilities are frequently cooled down and warmed up, and NMR magnets also need to be trained routinely in the MTA I and MTA II test facilities, all facilities were integrated into closed He I refrigeration circuits with the Linde 300 W plant. The comparatively low He IIp subcooling capacity in the magnet bath is generated by expansion and HEX units installed in the cryostat; the vapor produced in the He IIs auxiliary HEX bath is extracted by vacuum pumps. Table 5 shows the present cooling circuits and test facilities integrated in the ITP interconnected helium facility system.

6.4. Cooling techniques, helium circulation techniques

In the early superconductivity projects, the magnets and cavities as test objects were cooled in saturated He baths. More powerful superconducting magnets indicated rather early the limits and risks of cooling by He I baths (location-dependent heat transfer, degradation of heat transfer in blind-end channels, change and obstruction of heat transfer by vapor formation). On the other hand, the advantages of He IIs bath cooling (extremely high thermal conductivity without bubble formation, location-independent heat transfer) were exploited in cooling various RF resonators and RF input and output elements.

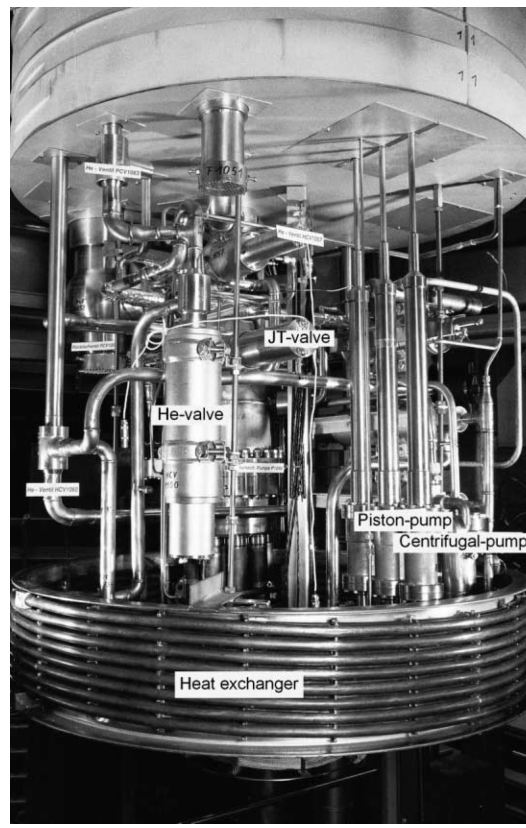


Fig. 34. TOSKA facility: the He II (He II HEX) cryostat inserts with HEX, piston, centrifugal and thermo mechnical pump (left hand behind the He valve).

Extensive studies and development work have been performed on helium forced-flow-cooling. In the HELITEX facility, the attraction and special features of supercritical forced-flow-cooling have been studied in long superconducting cable models, and quantified under steady-state, transient and off-normal load condi-

Table 5
ITP cooling circuits and test facilities

Test facility	Test object/object to be cooled	Refrig. circuit with/LHe supply from	Cryostats	In operation since
TOSKA	Fusion magnets		175 m^2 test dewar	
	ffc 4.4/3.3 K	2 kW He I Refr.	3000 l He I HEX Cryost.	1984
	ffc 1.8 K	300 W He II Refr.	1000 l He II HEX Cryost.	1996
TESPE/STAR	Fusion magnets 4.4 K	2 kW He I Refr. or 300 W He I Refr.	18 m^3 test dewar with two separated LHe tanks	1981/1993
TIMO	ITER model cryopumps ffc 4.4 K	2 kW He I Refr. or 300 W He I Refr.	10 m^3 test dewar 3000 l He I HEX Cryost.	2000
FBI 10/100 kN	SC probes 4.2 K bath cool ing	LHe from 5000 l storage at 300 W Refr.	He I bath cryostat	1993
JUMBO	15 T magnet SC probes 4.2 K bath cooling	LHe from 5000 l storage at 300 W Refr.	He I bath cryostat	1979
HOMER I	20 T magnet syst. 1.8 K He II_p bath	300 W He I Refr. + He II subcooler 10 W	250 l He II_p cryostat with therm. barrier	1983
HOMER II	20 T magnet syst. (1) 25 T magnet syst. (2) 1.8 K He II_p bath	300 W He I Refr. + He II subcooler 25 W	300 l He II_p cryostat with therm. barrier	2001 (cryosystem)
MTA I	NMR magnets 750/800/900 MHz T_λ He II_p bath	300 W He I Refr. + He II subcooler 15 W	250 l He II_p cryostat with therm. barrier	1989
MTA II	Highest field magnets $\leqslant T_\lambda$ He II_p bath	300 W He I Refr. + He II subcooler	He II_p cryostat with therm. barrier	To be constructed

tions. The positive findings constituted the basis for the decisions on the construction of the forced-flow-cooled EURATOM LCT coil, whose stability characteristics were excellent, as described above under all conditions of use (in TOSKA at 4.4 K, in the Oak Ridge National Laboratory test facility at 3.8 K, in TOSKA at 1.8 K) [16,25,119].

To this day, helium forced-flow-cooling of large fusion magnets has been practiced at ITP within autonomous closed secondary cooling circuits employing cold pumps for helium circulation [120]. Extensive findings were generated by specific comparative thermohydraulic studies in the HELITEX facility: the advantages and drawbacks of direct cooling with the Joule Thomson flow of the refrigerator and within a closed secondary loop, delivery characteristics of piston and centrifugal circulator pumps, cooling stability under transient heat loads as a function of cooling circuit configuration and circulator pump characteristic [121].

The high-capacity circulator pumps used (single-cylinder and three-cylinder designs with mass flows up to 150 g/s and pressure heads up to 4 bar) were developed jointly with industry and subjected to extensive trial runs in the HELITEX facility [122,123]. For lower cooling capacity requirements (up to 50 g/s and 0.4 bar), centrifugal LHe immersed pumps with magnetic bearings and superconducting drive developed at the Walther-Meissner Institut, Munich, were redesigned and upgraded to match ITP's systems and operating conditions. All of these mechanical pumps were used very successfully both in normal fluid, mostly supercritical, He I conditions and in subcooled, superfluid He II conditions (in the 11 T operation of the mechanically reinforced EURATOM LCT coil). These pumps proved to be able to pump and circulate He II without any deterioration of the delivery characteristics [124].

Prior to the development of the POLO model coil, which was operated in a dual cooling mode ensuring stable and effective quasi-isothermal cooling of the superconducting cable, cryogenic investigations of two-phase He I forced-flow-cooling were carried out in three stages:

1. Experiments with a quasi-horizontal test channel 200 m long and 10 mm in diameter to study flow behaviour and heat transfer characteristics.
2. Thermohydraulic studies of four parallel quasi-horizontal channels equipped with heaters and mass flow control circuits to simulate the four pancakes of the model coil.
3. Simulation, by pulsed thermal loads, of AC losses due to plasma control in a reactor, and observation of the effects on cooling effectiveness.

Optical observation of the flow indicated a typical wavy flow or a typical stratified flow. Despite separately flowing phases, the homogeneous computation model turned out to be sufficiently accurate for pressure drop estimates [125].

Pulsed thermal operation resulted in case of a flow generated by a "natural" pressure gradient in dangerous operation conditions with complete stoppage of flow and even flow reversal. Here the use of a piston pump to force the two-phase flow through the channels enabled a sufficiently stable forward flow. The advantage of this solution was confirmed during the operation of the POLO model coil [27].

Bath cooling in superfluid subcooled He IIp baths proved to be a highly efficient cooling and stabilization technique for high-field magnets. For this reason, it is being applied at ITP at the boundary temperature, T_λ, and at the lower He II temperatures down to 1.6 K.

6.5. Cryostat techniques

The many requirements for RF and high-current superconductivity areas have necessitated individual special cryostats to be designed, manufactured, tested and operated in the Institute.

Initially, horizontal bath cryostats were chosen for a variety of high-energy physics applications. Their reliable and economic operation when filled with He I and He II also required experimental studies and development work to be performed in cooling process technology, sealing, measurement, thermal insulation and safety techniques. The experience accumulated in these fields has been used to this day in designing and building new cryosystems.

The change in activities that was associated with a discontinuation of RF superconductivity and a concentration on fusion magnets, high-field magnets, and energy technology, required other types of cooling techniques, and also different vertical cryostat designs.

Fusion magnets with forced-flow-cooling demand cryostat designs with spacial separation of the functions of thermal insulation of the forced-flow-cooled magnet (test dewar) and the refrigerant bath with the cryoreservoir (LHe HEX cryostat with thermal coupling point between the primary and secondary helium circuits, see Figs. 34 and 35) and also with the new designs with very powerful gaseous He forced-flow-cooled current leads [39].

The other type of cryostat design now customarily used at ITP is the vertical wide-neck cryostat with thermal barrier. This type is used for all of the ITP high-field magnets, e.g. in the HOMER II facility (Fig. 36). The He I reservoirs above the thermal barrier of these cryostats are supplied by the He I refrigerator plant. Part of the flow is fed to the He II subcoolers, whose expansion and HEX units are located in the magnet baths below the thermal barrier; the exhaust vapor of the HEX operating with saturated He II is first warmed up to ambient temperature and then pumped off by conventional vacuum pumps and returned to the compressor of the refrigerator. This type of cryostat has been used successfully for many years in the high-field experimental and test facilities, HOMER I, MTA I, HOMER II and, in the future, MTA II. To limit the thermal load for the He II magnet bath, a tightly sealing thermal barrier is required for the HOMER plants operated at approximately 1.8 K. For MTA I, which is operated at the He II boundary temperature, T_λ, a simple convection barrier is sufficient, as the gaps in the region of this barrier contain only He I, whose thermal conductivity is low. Two different types of He II subcoolers were developed and compared in performance tests for subcooling of the magnet baths [126]. Both types have been run successfully for years.

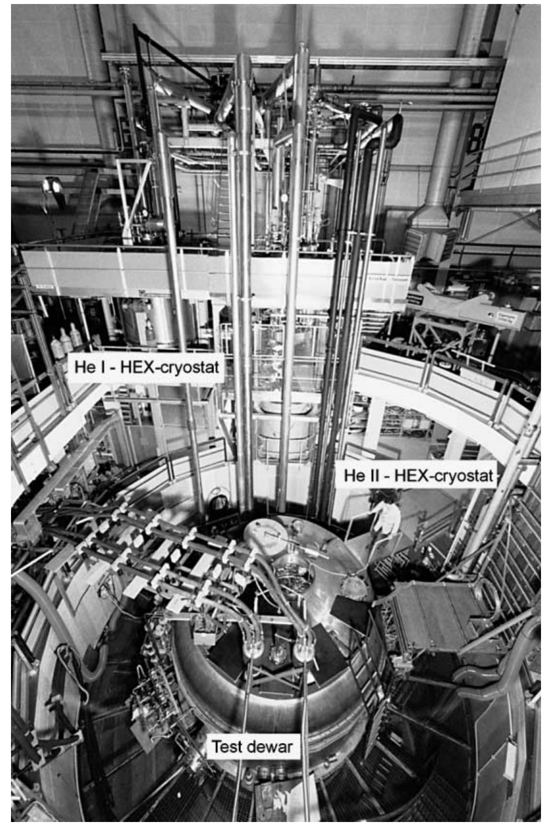


Fig. 35. TOSKA facility with test dewar and HEX cryostats in the background.

The development, design, and test work for the low loss prototype cryostat of the Bruker high-resolution NMR spectrometers conducted at ITP required a different, more sophisticated cryostat technique. In this case, a low loss thermal barrier technique and optimum utilization of the He exhaust gas enthalpies were required to limit the overall consumption of the cryostat below 100 ml/h to be supplied intermittently from LHe transport containers [127, Pat.].

6.6. Thermal insulation

Thermal insulation with MLI (multilayer insulation) as employed in He cryogenics allows the maximum attainable quality of insulation to be achieved. Because of the anisotropy of MLI and the difference from an ideal configuration in the form of highly reflective shields freely floating in high vacuum, MLI may undergo tremendous degradation when installed in cryoequipment. This is particularly true of three-dimensional surfaces,

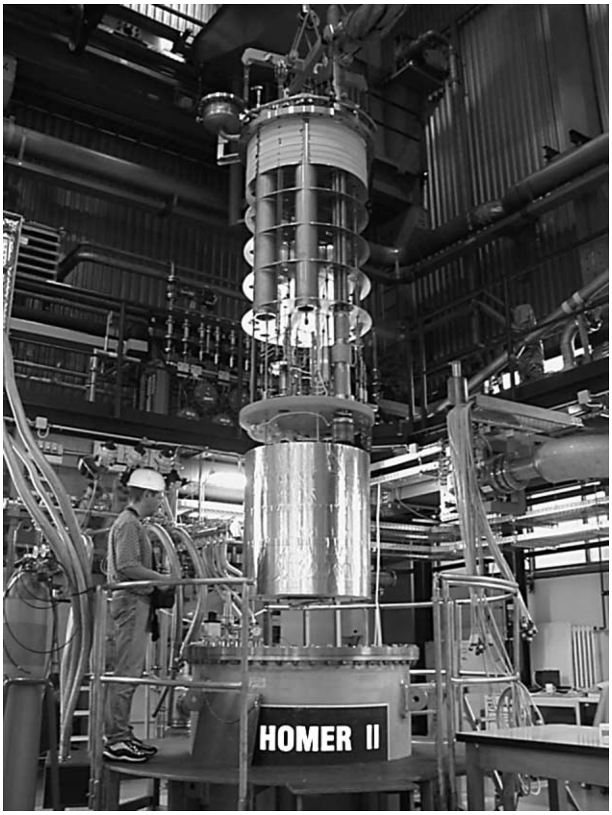


Fig. 36. HOMER II cryostat during installation of the magnet system (Fig. 11).

surfaces with interruptions and penetrations, components with small diameters, difficult access, etc. Unsatisfactory experience with purchased and in-house cryoapparatus and transfer lines required in-house studies to be performed.

In a mid-size test facility (TESSI/THISTA) built for this purpose, studies between RT and 80 K, and RT and 4 K, respectively, were carried out, first mainly with reference to large scale cryostat technique, then later to cryotransfer lines and "pipe cryostats" for HTS cables. This also included a choice of optimum available commercial MLI available for ITP applications and their characterization under the constraints of assembly and operation in various cryostat and cryotransfer line configurations [128].

The use of blanket MLI allowed the quality of the insulation to be enhanced considerably; this is particularly true for equipment of smaller diameter and for transfer lines [129].

Incidents such as damage to the vacuum vessel and subsequent venting with atmospheric air cause major to catastrophic deterioration in thermal insulation quality. In the 1970s, detailed studies of this type of failure were conducted in LHe cryostats and transport containers and produced basic design data for safety design of cryoequipment which have been applied to this day [130]. Supplementary measurements with superinsulated LN_2 equipment were carried out in the TESSI facility [131].

At present, experimental studies have been started in the THISTA facility to improve the insulation quality in flexible LN_2 cooled corrugated pipe cryostats for HTS cables by means of new, patented MLI techniques.

6.7. Cryomeasuring and cryoprocessing techniques

A cryosystem that is economic in use and safe and reliable in all modes of operation necessitates accurate and reliable measuring techniques. For this reason, experimental studies have always accompanied projects in order to design suitable low-temperature measurement techniques. Measured quantities of particular importance in cryoprocess management are the temperature, the pressure, the mass flow and the cryogen bath level. A multitude of sensors and actuators matching the requirements in each project have been used to conduct studies and optimize design. Specific constraints had to be taken into account, such as the influence of strong magnetic fields or stray fields, difficult conditions of installation and access, and ageing effects and the effects of temperature cycling. Recently, more detailed studies and developments of low temperature and mass flow measurements have been conducted (present activities with TVO temperature sensors and very small Venturi nozzles [132,133]).

For low-temperature sensor calibration, a helium calibration cryostat was designed for operation in the evaporator and bath modes, which has been modernized and automated over the years. At $1.5 < T < 300$ K it allows temperature sensor calibrations to be achieved with an accuracy of $\pm 0.3\%$ [134].

Logging, processing and visualizing measured data has undergone major changes and improvements. Throughout the cryofacility area, there have been continuous improvements, upgrading, and more and more automation. Very powerful process instrumentation and control systems were set up in cooperation with industry which achieve a high and reliable degree of automation in a variety of different modes of operation [126, 135]. Thus, e.g. the two Linde refrigeration plants, the TOSKA- and HOMER II-test facilities have been equipped with up-to-date and suitable computerized process control systems.

6.8. Special cryogenic developments

Some applications of superconductivity require specially developed cooling methods. For the forced-flow-cooling of magnets by He II a pump on the basis of the fountain effect was constructed and successfully operated. The so-called cryogen-free magnets need small, efficient and vibration free refrigerators which has been achieved by a pulse tube refrigerator. Outside of magnet technology, cryogenic vacuum pumps are being developed for the plasma exhaust system of ITER.

6.8.1. Thermo-mechanical pump for He II

Some applications, such as for the test of the reinforced EURATOM LCT at its outermost operation limits, need cooling by forced flow of superfluid helium. A very elegant method for circulating subcooled He II by using of the so-called fountain effect (thermo-mechanical effect) was developed in ITP and is schematically shown in Fig. 37 [136]. The circulation is driven by the heat picked up by the magnet. This method is most useful for internally cooled windings. Typically, helium with 1.8 K temperature is fed-in in the high-field region. The warmer helium leaving the magnet is guided through a HEX at the warm end of a porous plug, which is the main element of the pump. The pressure head of such pumps can be as high as 0.05 MPa, thus enabling to force sufficient helium flow through coolant channels of several 100 m in length. Experimental and theoretical models for the design of such cooling loops were initially developed for small-scale devices with about 1 g/s of He II flow. Based on those results, a large pump for operating the EURATOM LCT coil with about 20 g/s has been constructed and operated successfully [22]. Additional research has been done on heat transfer and on the friction loss of forced He II flow in different configurations of channels [137].

6.8.2. Pulse tube refrigerator

The commercialization of small and medium size superconducting equipment is calling for "invisible" refrigerators. Some of the drawbacks of conventional Stirling and Gifford McMahon (GM) coolers may be

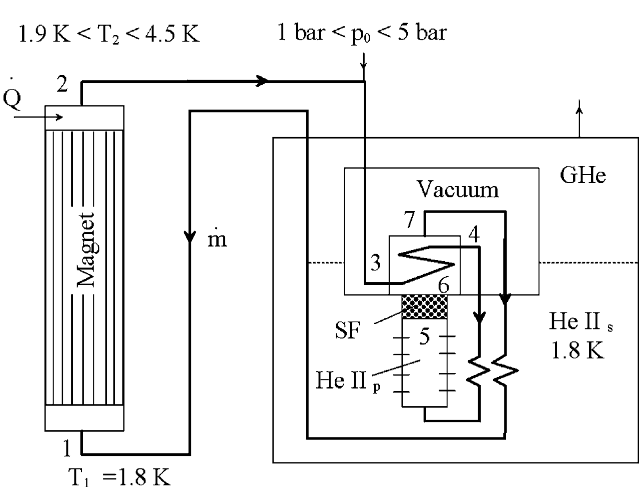


Fig. 37. Schematic of a forced flow cooling loop driven by a thermo mechanical pump. ($\dot{Q}$: heat removed from the magnet, $\dot{m}$: mass flow of circulating He II subcooled by externally applied pressure p_0, SF: porous plug with temperatures T_5 1.8 K and 1.8 K < T_6 < T_λ; He II: pool of saturated superfluid He; numbers 1, ..., 7 indicate the flow direction.

eliminated by pulse tube refrigerators. These pulse tube refrigerators have no moving components in the cold head, and promise the possibility of high reliability and low level of vibration. ITP's pulse tube development program began in the 1990s. The experimental facility as schematically shown in Fig. 38 has been designed for operation with a 6.5 kW scroll compressor, as used for conventional GM coolers. The cold head of the pulse tube refrigerator is presented in Fig. 39. Single and two stage arrangements can be realized simply by rearranging of the cold head components. Typical achievements are 90 W at 70 K for single stage operation, 10 W at 18 K together with 40 W at 45 K for a two stage system, and no-load temperatures below 4 K are achieved when a rare-earth material is used in the second stage regenerator [138]. It has been shown that the efficiency of such coolers is no longer far below that of conventional GM coolers. Pulse tube coolers are now ready as a substitute for GM coolers in many applications.

6.8.3. Cryogenic model vacuum pump for the plasma exhaust system of ITER

The objective of the working group "Vacuum technology for fusion" which joined the ITP in 1998, is the design, manufacturing and testing of the torus cryopumps to be used for evacuation of the ITER in all operation modes.

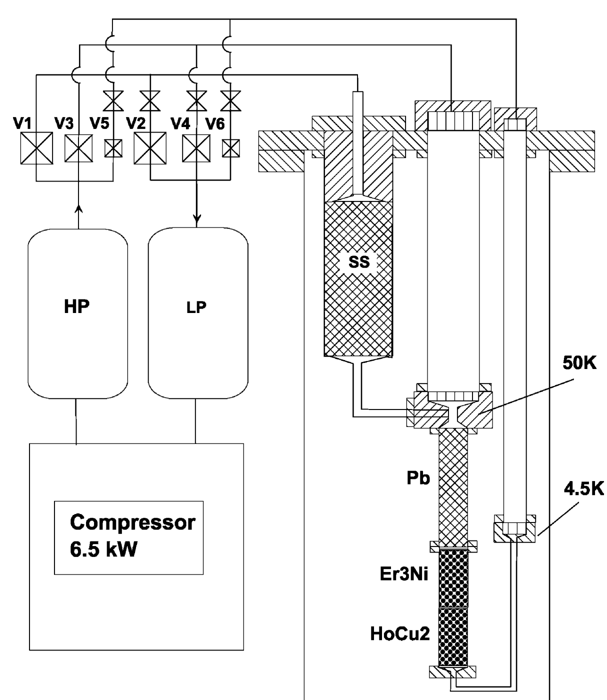


Fig. 38. Schematic of the two stage pulse tube cooler test facility. The gas flows at the ambient temperature end of regenerator and both pulse tube are controlled by open/close valves combined with throttling devices.

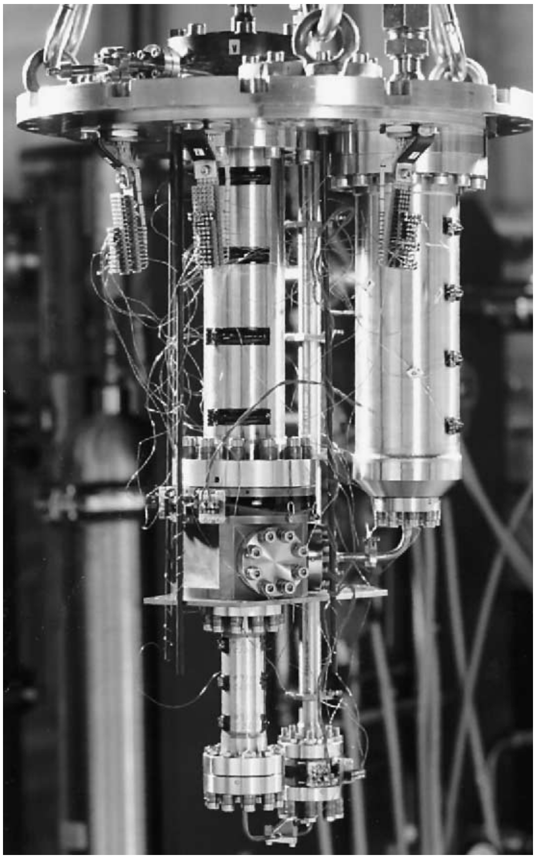


Fig. 39. The experimental set up of the pulse tube cooler.

Because of the challenging environment (e.g. high magnetic and radiation fields, tritium atmosphere, acceleration during disruption, sudden venting with air or steam under accidental conditions) and the need for high gas throughputs, no commercially available pumps can be used. On the basis of the ITER requirements, the advantages and disadvantages of known and approved vacuum pumping systems were analyzed and it was concluded that a new concept is required. Ten identical batch regeneration pumps have been selected for ITER, using cryosorption, of helium and some hydrogenic species, and cryocondensation of the other gas species in the torus exhaust [139,144].

The pump development programme includes both design and supporting R&D activities [142].

In preliminary screening tests, combinations of substrate, bonding and sorbent materials were optimized [139]. Thermal shock tests over 10,000 cycles in the temperature range between 300 80 K and 80 4.5 K demonstrated the qualification of the pumping panels in 1:2 scale compared to the prototype pump. Component tests with the pumping panels to study the pumping speed, capacity and poisoning with single gases and ITER-relevant gas mixtures were performed.

Following this successful demonstration on the reduced size panels, a 50% full size model with an integral

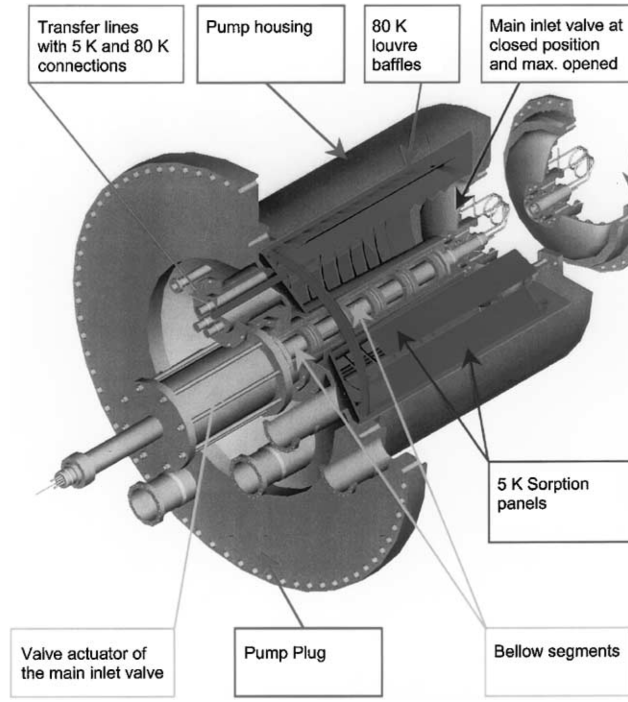


Fig. 40. 3D View of ITER model pump.

inlet valve has been designed and manufactured in cooperation with the company Air Liquide, Sassenage, France. The cryopump as shown in Fig. 40 is designed on the basis of a cylindrically shaped housing with 1200 mm diameter and a length of 1360 mm [145]. The

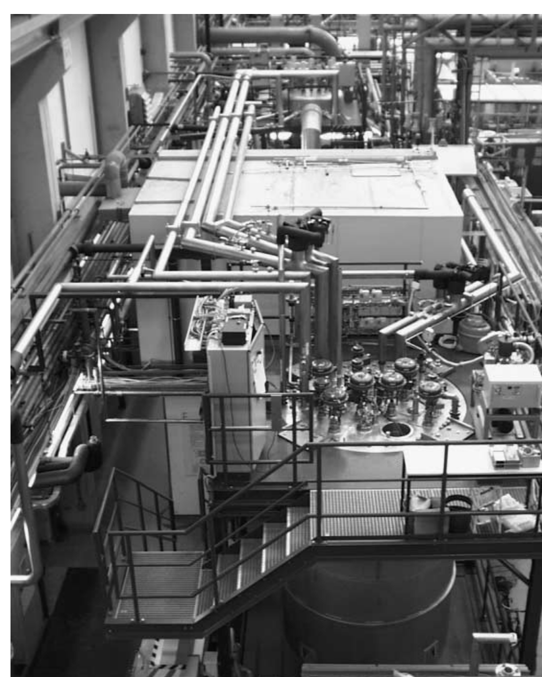


Fig. 41. TIMO facility showing 3000 l control cryostat and cryo transfer line to cold valve boxes.

diameter of the valved inlet port is 700 mm. Gas particles entering the pump impinge on an optically tight baffle arrangement cooled at 80 K by gaseous helium. The impurity gases with high-boiling point are condensed on these surfaces. Hydrogen isotopes, helium and the remaining impurities pass the baffle and are cosorbed on a set of 16 activated charcoal-coated panels maintained at 5 K. The pumping panels are arranged on a radius of 450 mm to the pump axis. They are inclined by 45° to achieve maximum pumping efficiency. The 5 K panels are completely surrounded by 80 K shields and the 80 K baffle in order to avoid thermal radiation from the outer shell of the pump, the valve disk and the shaft.

At the same time, the TIMO facility (Fig. 41) was built which enables studying the cryogenic and vacuum characteristics of the pump [143]. The pump itself is installed in a vacuum vessel designed according to the PNEUROP rules [146]. The needed average cooling power at 4.5 K temperature level is supplied by the 600 W Linde refrigerator. A control cryostat with a 3000 l liquid helium inventory is used as a buffer system. The 80 K gaseous He supply consists of a closed loop maintained at constant temperature by a HEX dipped into a liquid nitrogen bath.

During the parametric tests, the ITER requirements concerning pumping speed, gas load and throttling behaviour were achieved [140,141]. Cycling tests with the upgraded 3000 l control cryostat are under way, to verify the ITER-relevant regeneration times, cycle numbers and temperature distribution across the pumping panels.

7. Summary

The development of superconducting magnet technology has brought encouraging progress over 30 years, during which the ITP has made substantial contributions. Breakthroughs in the early 1970s and again in the second half of the 1980s, with the discovery of the HTS, have not been achieved in all areas up to now. But in several areas high-current superconductors and superconducting magnet technology were essential to further progress.

- In the frame of international collaborations, the superconducting magnet technology has been made available for the next generation of fusion experiments (W 7-X, ITER) with magnetic confinement.
- The ITP has supported by its high-field magnet research, development and test facilities an industrial partner to become one of the world leaders in high-resolution NMR spectrometers.
- For industrial application, LTS magnet technology was successfully applied in field tests of a magnetic separator and of a small SMES system. For a superconducting rotor of a turbo generator, a helium cooling circuit was developed. Devices for electrical power systems with HTS material are under development.
- The LTS materials NbTi and Nb_3Sn are in a very advanced state of their development. Suitable HTS conductor concepts are developed for application in electrical power technology. They are successfully applied in demonstrations.
- The fusion magnet development stimulated the creation of a cryogenic structural material data base by the adaptation and development of the measuring techniques at cryogenic temperatures. The developed equipment and results are unique around the world.
- An extended cryogenic infrastructure has been stimulated by the superconducting magnet projects. Large quantities of liquid helium and cold helium mass flows can be handled reliably and with acceptable losses. Forced-flow-cooling has been developed and mastered in the typical temperature range of superconducting magnet operation from 1.8 to 4.6 K. Bath cooling with subcooled superfluid helium has been applied successfully for high-field superconducting magnets. The cryogenic supply system and all test facilities are capable to run in steady state or standby mode in unattended operation.

  Research and special developments improve continuously cryogenic technology, e.g. 1.8 K cryostats, high-quality superinsulation techniques, cold helium circulators and small on-board refrigerators.

  On the basis of the existing cryogenic infrastructure, the development of a cryogenic vacuum pump for the ITER exhaust system has been integrated in 1998 in the ITP and the pump has started its operation in the TIMO facility.

All research and development work as well as all projects of the ITP have been included in national and international collaboration with other research organizations and industry. The ideas for collaborations combined with integration and management work has been the merit of P. Komarek, who has created with this the basis for successful projects supported by research and development.

Acknowledgements

The authors acknowledge the work of all collaborators inside and outside FZK, as well as European industry contributions to the success of these projects.

References

[1] Komarek P, Krauth H, Lehmann W, Wuhl H. World wide cryogenics Kernforschungszentrum Karlsruhe. Cryogenics 1984; 24:603 21.

[2] Komarek P. Hochstromanwendung der Supraleitung, Teubner Studienbucher, B.G. Teubner, Stuttgart, 1995.
[3] Komarek P. TASKA A tandem mirror fusion engineering test facility. In: 9th Plasma Phys and Contr Nucl Fus, IAEA, Vienna 1983, vol. II, p. 427 37.
[4] Mori S. INTOR. In: 11th Plasma Phys and Contr Nucl Fus, IAEA, Vienna 1987, vol. III, p. 195 245.
[5] The NET Team. Next European Torus (NET). Fusion Technol 1988;14(1):58 81.
[6] Sapper J. Superconducting coil development for the Wendelstein 7 X stellarator. Fusion Eng Des 1993;20:23 32.
[7] The NET Team. Next European Torus (NET). Fusion Eng Des 1993;21:107 64.
[8] ITER Joint Central Team and Home Teams. ITER Technology R&D. Fusion Eng Des 2001;55(2 3):139 90.
[9] Komarek P. The impact of fusion on superconducting magnet development in Europe. Fusion Eng Des 1993;20:291 7.
[10] Maurer W. Large scale superconducting magnet technology at the KfK Karlsruhe. Fusion Eng Des 1993;20:15 22.
[11] Jungst KP, Friesinger G, Geiger W, Grunhagen A, Kiesel H, Komarek P, et al. Sperconducting Torus "TESPE" at design values. In: Proc MT 9, Zurich, Switzerland, September 9 13, 1985. p. 36 9.
[12] Geiger W. Magnetoelastisches Buckling in suprleitenden toroid alen Magnetsystemen, Kernforschungszentrum Karlsruhe, KfK 4260, Marz, 1987.
[13] Kronhardt H. Einfluß von Kurzschlussen und Lichtbogen auf die Sicherheit von Magnetsystemen, Kernforschungszentrum Karls ruhe, KfK 5096, Mai, 1993.
[14] Jungst KP, The W 7 X Technical Group. Superconducting model coil for the stellarator W 7 X under test. IEEE Trans Magn 1996;32:2296 9.
[15] Heller R, Maurer W. Test results for an advanced conductor for the Wendelstein 7 X magnet system. IEEE Trans Appl Superc ond 2000;10(1):614 7.
[16] Beard DS, Klose W, Shimamoto S, Vecsey G. The IEA Large Coil Task. Fusion Eng Des 1988;7(1&2).
[17] Komarek P, Salpietro E. The test facility for the ITER TF model coil. Fusion Eng Des 1998;41:213 21.
[18] Ayai N, Yamada Y, Mikumo A, Sato K, Koizumi N, Sugimoto M, et al. Development of Nb_3Al cable in conduit fusion superconductors. IEEE Trans Appl Supercond 1995;5(2): 893 6.
[19] Krauth H, Nyilas A, Ries G, Schmidt C, Hillmann H, Rudolf J. Development and testing of a forced flow cooled superconductor for LCT. In: Proc Eng Probl of Fus Res 8. Symp, San Francisco, CA, USA, November 13 16, 1997.
[20] Krafft G. Helitex a test facility for large scale cooling exper iments with liquid helium. In: Proc ICEC 7, vol. 7. Guildford: IPC Science and Technology Press; 1978. p. 705 6.
[21] Schmidt C. Stability tests on the EURATOM LCT conductor. Cryogenics 1984;24:653 6.
[22] Darweschsad M, Fink S, Friesinger G, Grunhagen A, Heller R, Hofmann A, et al. Test of the EURATOM LCT Coil NbTi conductor with forced flow He II. Fusion Eng Des 1999;45:361 75.
[23] Heller R, Darweschsad M, Fink S, Friesinger G, Herz W, Maurer W, et al. Operation limits of the EURATOM LCT coil at forced flow He II temperature. Cryogenics 1998;38:519 24.
[24] Hofmann A et al. Design of a fountain effect pump for operating the EURATOM LCT coil with forced flow of helium. In: Advances in cryogenic engineering, vol. 37A. Pergamon Press; 1992. p. 139 46.
[25] Darweschsad M, Friesinger G, Grunhagen A, Heller R, Herz W, Kneifel B, et al. The test of the EURATOM LCT coil at the outermost limits at 1.8 K as example of single coil testing of D shaped toroidal filed coils. In: Proc MT 15, October 20 24. Beijing, China: Science Press; 1997. p. 373 6.
[26] d'Alencon M, Bareyt B, Cortial H, Leloup C, Rey G, Rijnoudt E, et al. The TORE SUPRA poloidal field coil system. In: 12th SOFT, Julich, Germany, September 13 17, 1982. p. 1165 71.
[27] Darweschsad M, Friesinger G, Heller R, Irmisch M, Kathol H, Komarek P, et al. Development and test of the poloidal field prototype coil POLO at Forschungszentrum Karlsruhe. Fusion Eng Des 1997;36:227 50.
[28] Heller R, Maurer W, Schoenewolf I, Ulbricht A, Wuchner F, Zahn G. Abschlußbericht zum Test der Wendelstein 7 X (W 7 X) Demonstrationsspule in TOSKA, Forschungszentrum Kar lsruhe, Wiss. Berichte, FZKA 6486, Juli, 2000.
[29] Heller R, Maurer W, Sapper J, Schauer F, Schoenewolf I, Ulbricht A, et al. Test results from the Wendelstein 7 X stellarator demonstration coil. Cryogenics 2000;40:561 7.
[30] Flukiger R, Heller R, Komarek P, Maurer W, Klemm M, Leimbach KR, et al. Development of the KfK NET toroidal field coil react and wind conductor, Kernforschungszentrum Kar lsruhe, KfK 4777, September, 1990.
[31] Specking W, Nyilas A, Klemm M, Kling A, Flukiger R. The effect of axial stresses on I_C of subsize NET Nb_3Sn conductors. In: Proc MT 11, Tsukuba, Japan, August 28 September 1, 1998. p. 1009 14.
[32] Erb J, Grunhagen A, Herz W, Horvath I, Jentzsch K, Komarek P, et al. NET model coil test possibilities, Kernforschungszen trum Karlsruhe, KfK 4355, November, 1987.
[33] Grunhagen A, Heller R, Herz W, Hofmann A, Jentzsch K, Kapulla H, et al. NET model coil test possibilities in the TOSKA TWIN configuration, Kernforschungszentrum Karlsruhe, KfK 4602, July, 1989.
[34] Salpietro E, Maix R, Bevilacqua G, Mitchell N, Turck B, Ulbricht A, et al. The ITER toroidal field model coil develop ment programme. In: 17th IAEA Fus En Conf Yokohama, Japan, October 19 24, 1998.
[35] Maix R, Fillunger H, Palmer J, Salpietro E, Mitchell N, Decool P, et al. Completion of the ITER toroidal field model coil. In: Proc 21st SOFT. Fusion Eng Des, Part B 2001;58 59:159 64.
[36] Fillunger H, Hurd F, Maix RK, Salpietro E, Ciazynsky D, Duchateau JL, et al. Assembly in the test, acceptance, and first results of the ITER TF model coil. In: Proc. MT 17, Geneva, Switzerland, September 24 27, 2001.
[37] Bauer K, Fink S, Friesinger G, Ulbricht A, Wuchner F. The electrical insulation system of a forced flow cooled supercon ducting (sc) magnet. Cryogenics 1998;38:1123 34.
[38] Nother G, Gauss S, Maurer W, Siewerdt L, Ulbricht A. Quench detection system for the EURATOM LCT coil for the Large Coil Task. Cryogenics 1989;29:1148 53.
[39] Heller R, Fink S, Friesinger G, Kienzler A, Lingor A, Schleinkofer G, et al. Development of forced flow current leads for fusion magnets. Cryogenics 2001;41:201 11.
[40] Heller R, Friesinger G, Fuchs AM, Mito T, Satoh S, Takahata K, et al. Development of a 20 kA high temperature supercon ductor current lead. Cryogenics 2001;41:539 47.
[41] Heller R, Friesinger G, Fuchs AM, Wesche R. Development of high temperature superconductor current leads for 70 kA. In: Proc MT 17, Geneva, Switzerland, September 24 27, 2001.
[42] Turowski P, Schneider Th. A 20 T superconducting magnet system. Physica B 1989;155:87 90.
[43] Komarek P, Lehmann W, Schneider Th, Turowski P, Laukien G, Roth G. KfK Nachrichten 1993;25:73 83.
[44] Rimikis A, Kimmich R, Schneider Th. Investigation of n values of composite superconductors. IEEE Trans Appl Supercond 2000;10:1239 42.
[45] Rimikis A, Hornung F, Schneider Th. High field magnet facilities and projects at the Forschungszentrum Karlsruhe. IEEE Trans Appl Supercond 2000;10:1542 6.

[46] Hornung F, Rimikis A, Kimmich R, Schneider Th. Investigation of Bi HTS wires for high field insert coils. IEEE Trans Appl Supercond 2000;11:2304 7.
[47] IEA Implementing Agreement for a Co Operative Programme for Assessing the Impacts of High Temperature Superconductivity on the Electric Power Sector. Papers available within Germany from K.P. Juengst, ITP, Forschungszentrum Karlsruhe, D 76021 Karlsruhe.
[48] Jungst KP, Ries G, Forster S, Graf F, Obermaier G, Lehmann W. Magnet system for a superconducting magnetic separator. Cryogenics 1984;24:648 52.
[49] Unkelbach KH, Wasmuth HD. A superconductive drum type magnetic separator for the beneficiation of ores and minerals in commercial scale. Colloquium on Magnetic Separation, Mintek 1986, January 30 31, Johannesburg, South Africa.
[50] Franzreb M, Jungst KP, Franz M, Holl W, Eberle S. Hochgradi enten Magnetabscheider, patent EP PS 59702706, December 6, 2000.
[51] Franzreb M, Watson JHP. Elimination of heavy metals from waste waters by magnetic technologies. In: SenGupta AK, editor. Environmental separation of heavy metals: engineered processes. London, UK: CRC Press; 2001. ISBN: 1 5667 6884 5.
[52] Hofmann A. Investigations on self pumping cooling systems for superconducting generators. In: Proc XVIth Int. Congress of Refrigeration (IIR XVI), Paris, 1983. p. 117.
[53] Schnapper Ch. Warmetransport und Warmeubergang mit He lium in rotierenden Kanalen. Dissertation Universitat(TH) Karlsruhe 1978, und KfK Report 2654, 1978.
[54] Laskaris TE. A cooling concept for improved field winding performance in large superconducting ac generators. Cryogenics 1977:201 8.
[55] Lambrecht D. Status of development of superconducting AC generators. IEEE Trans Magn 1981;17:1551 9.
[56] Juengst KP, Komarek P, Maurer W, editors. Use of supercon ductivity in energy storage. Singapore: World Scientific; 1995. ISBN 981 02 2182 7.
[57] Simon H, Spath H, Salbert H, Juengst KP, Komarek P. Experimental experiences of a shunt active filter with supercon ducting magnetic energy storage (SMES) to enhance quality of power supply. In: ETG/EUREL Conference on Quality of Power Supply, Munich, Germany, November 17 18, 1997.
[58] Juengst KP, Gehring R, Kudymow A, Pfisterer HJ, Suess E. SMES compensator with a toroidal magnet system. In: Proc 17th Intern Conf on Magnet Technology, Geneve, CH, September 24 28, 2001.
[59] Salbert H, Juengst KP. Modulator zur Erzeugung eines elektris chen Pulses hoher Leistung, patent EP PS 59503207, August 12, 1998.
[60] Juengst KP, Gehring R, Kudymow A, Kuperman G, Suess E. 25 MW SMES based power modulator. In: Proc 17th Intern Conf on Magnet Technology, Geneve, CH, September 24 28, 2001.
[61] Noe M, Juengst KP, Werfel FN, Elschner S, Bock J, Wolf A, et al. Measurements and tests of HTS bulk material in resistive fault current limiters. In: 5th European Conference on Applied Superconductivity, Copenhagen, DK, August 26 30, 2001.
[62] Noe M, Juengst K P, Werfel FN, Elschner S, Breuer F, Bock J, et al. Testing bulk HTS modules for resistive superconducting fault current limiters, ASC Houston, USA, August 4 9, 2002.
[63] Erb J, Heinz W, Heller I, Hofmann A, Kofler HJ, Komarek P, et al. Comparison, of advanced high power under ground cables designs, Iinsitut fur Experimentelle Kernphysik, Kernfors chungszentrum Karlsruhe, European Communities Commission contract no. 80 73 12 ECID, September, 1974.
[64] Norman S, Nassi M, Ladié P, Poehler S, Schroth R. Design and development of cold dielectric (CD) high temperature supercon ducting cable systems for bulk power transmission at voltages up to 225 kV. In: CIGRÈ Conference, Paris, France, 2000, paper 21 205.
[65] Bauer K, Fink S, Huber D, Ulbricht A, Zwecker V. Aufbau und Inbetriebnahme zur Isolationsprufung an Hochtemperatursupr leitenden Kabelkurzproben fur die EnergieTechnik (HAIhKE), VDI Tagungsband, Supraleitungs u. Tieftemperaturtechnik, Statusseminar, October 19 20, 1998.
[66] Drost E, Specking W, Flukiger R. Comparison of superconduct ing properties and residual resistivities of bronze processed Nb_3Sn wires with Ta, Ti and Nb + Zn additives. Cryogenics 1984;24:622; IEEE Trans Magn 1985;MAG 21:281.
[67] Goldacker W, Flukiger R. Phase transitions and superconduct ing properties of binary and Ti, Ta, Ga, and H alloyed Nb_3Sn. Physica B+C 1985;135:359.
[68] Xu JQ, Specking W, Obst B, Seibt E, Flukiger R. Superconducting and metallurgical properties of Nb_3Sn wires processed by internal tin route including hydrostatic extrusion. Cryogenics 1989;29:87 95.
[69] Gauss S, Flukiger R. Powder metallurgical alternative for the processing of $(Nb\ Ta)_3$ Sn multifilamentary wires, starting from elementary Nb and Ta powder. IEEE Trans Magn 1987;MAG 23:657.
[70] Flukiger R, Goldacker W. Physical, metallurgy and critical currents in Nb_3Al multifilamentary wires. In: Marinucci C, Weymuth P, editors, Proc MT 9 Zurich, 1985, Swiss Inst of Nucl Res. p. 553.
[71] Specking W, Flukiger R. A compact 5 kN test facility for superconducting conductors carrying up to 1.5 kA in magnetic fields up to 14 T. J Phys 1984;45 C1:79 81.
[72] Specking W, Goldacker W, Flukiger R. Effect of transverse compression on I_C of Nb_3Sn multifilament wire. Adv Cryog Eng 1988;34:569 75.
[73] Goldacker W, Specking W, Weiss F, Rimikis G, Flukiger R. Effect of axial tensile and transverse compressive stress on J(sub)c and Bsub(c2) of $PbMo_6S_8$ and $SnMo_8S_8$ wires. Adv Cryog Eng 1990;36:955.
[74] Ullmann B, Gabler A, Quilitz M, Goldacker W. Critical transport current of Bi(2 2 2 3)/Ag and AgMg multifilamentary tapes for current leads, EUCAS 97, Eindhoven NL, IOP Conf Ser No 158, vol. 2, 1997. p. 1259.
[75] Flukiger R, Goldacker W. The origin of prestress in binary and ternary Nb_3Sn multifilamentary wires. IEEE Trans Magn 1985;MAG 21:807 10.
[76] Goldacker W, Rieger C, Maurer W. Calculated stress distribu tion in a $PbMo_6S_8$ wire performing the I_c vs. epsilon experiment. IEEE Trans Magn 1991;27:946 9.
[77] Rimikis G, Goldacker W, Specking W, Flukiger R. Critical currents in $Pb_{1.2\ x}Sn_xMo_6S_8$ wires. IEEE Trans Magn 1991;27: 1116 9.
[78] Goldacker W, Kessler J, Wildgruber U, Bluem S. High critical currents in Bi(2 2 2 3) tapes with Ag and hardened Ag sheats, MRS Fall meeting Strasbourg, France November 1992. J Alloys Compd 1993;195:511 4.
[79] Goldacker W, Nast R, Krelaus J, Heller R, Taska M. Properties of low thermal loss multifilamentary BSCCO(2 2 2 3) tapes with AgMg/AgAu sheath for current leads. Adv Cryog Eng 2000; 46B:785.
[80] Goldacker W, Quilitz M, Obst B, Eckelmann H. Novel resistive interfilamentary carbonate barriers in multifilamentary low AC loss Bi(2 2 2 3) tapes. Physica C 1998;310:122.
[81] Krelaus J, Nast R, Eckelmann H, Goldacker W. AC losses of multifilamentary Bi(2 2 2 3) tapes in external perpendicular mag netic fields with resistive barrier structures between the filaments. IOP Conf Ser No. 167, 2000. p. 727.
[82] Nast R, Obst B, Goldacker W, Schauer W. Recrystallization of nickel and Ni alloy substrates for YBCO coated conductors. In: MRS Fall meeting Boston 2000, Proc, vol. 659, 2001. p. II10.3.1.
[83] Goldacker W, Schlachter SI, Zimmer S, Reiner H. High transport currents in mechanically reinforced MgB_2 wires. Supercond Sci Technol 2001;14:787 93.

[84] Nast R, Schlachter SI, Goldacker W, Zimmer S, Reiner H. Mechanically reinforced monofilamentary MgB_2 PIT wires with very high transport critical current densities. Physica C 2002;372 376:1241 4.
[85] Schlachter SI, Fietz WH, Grube K, Goldacker W. High pressure studies of T_c and lattice parameters of magnesium diboride. Adv Cryog Eng 2002;48B:809 16.
[86] Goldacker W, Schlachter SI. Mechanically reinforced monofil amentary MgB_2 wires with high transport currents. Physica C 2002;378 381:889 93.
[87] Dietrich M, Schneider H, Thorwarth E, Weidemann R. High pressure structure investigation of Nb_3Sn, Nb_3Al, Nb_3Ir, and Nb_3Ge, in superconductivity in d and f band metals. In: Buckel W, Weber W, editors. Proc on the IV Conference, Karlsruhe. 1982. p. 45 8.
[88] Krevet B, Schauer W, Wuchner F, Schulze K. Nucleation and growth of high T_c Nb_3Ge co evaporated films. Appl Phys Lett 1980;36:704 6.
[89] Obst B. Basic aspects of tensile properties. In: Seeber B, editor. Handbook of applied superconductivity, vol. II. IOP Publishing; 1998. p. 969 93.
[90] Dietrich M, May D, Seibt E, Runtsch B. Niobnitrid Supraleit erEntwicklung auf Faserbasis. KfK Nachrichten 1989;21:54 9.
[91] Breit V, Schweiss P, Hauff R, Wuhl H, Claus H, Rietschel H, et al. Evidence for chain superconductivity in near stoichiometric $YBa_2Cu_3O_x$ single crystals. Phys Rev B 1995;52:R15727.
[92] Schlachter SI, Fietz WH, Grube K, Wolf Th, Obst B, Schweiss P, et al. The effect of chemical doping and hydrostatic pressureon T_c of $Y_{1\ y}Ca_yBa_2Cu_3O_x$ single crystals. Physica C 1999;328:1 13.
[93] Meier Hirmer R, Kupfer H, Scheurer H. Experimental study on the collective theory of flux pinning in a high field superconduc tor. Phys Rev B 1985;31:183 92.
[94] Arita M, Nissen HU, Kitano Y, Schauer W, Stenzel M. Electron microscopy of grain boundaries of Nb_3 Ge with the A15 structure. Phys Status Solidi A 1996;157:379 92.
[95] Kupfer H, Wolf Th, Lessing C, Zhukov AA, Lancon X, Meier Hirmer R, et al. Peak effect and its evolution from oxygen deficiency in $YBa_2Cu_3O_{7\ \delta}$ single crystals. Phys Rev B 1998;58:2886 94.
[96] Neumann J, Mutterer R, Schauer W, Grube K, Schiller HP, Re iner J, et al. Angular dependence of the irreversibility temperature for Y and Nd BaCuO. Physica B 2000;284 288:695 6.
[97] Schauer W, Schiller HP, Grube K, Reiner J. Inductive test of the critical current homogeneity of long Bi 2223 tapes. In: Science and engineering of HTC superconductivity.Vincenzini P, editor. Advances in science and technology, vol. 23. 1999. p. 117 24.
[98] Wittgenstein F. La realisation de L'aimant superconducteur de la chambre à bulles europeenne (BEBC), Industries Atomique no 5/ 6, 1970. p. 3 16.
[99] Nishimura A, Yamamoto J, Nyilas A. Fatigue crack growth of SUS 316 and weld joint with natural crack at 7 K. In: Balachandran UB et al., editors. Advances in cryogenic engi neering (materials), 44A. New York: Plenum; 1998. p. 81 8.
[100] Komarek P, Nyilas A, Obst B, Zhang J. High resolution extens ometers for use in cryogenic environment. In: 18th International Congress of Refrigeration, Montreal, August 10 17, 1991.
[101] Nyilas A. Guidelines for the tensile measurements of supercon ducting tapes and wires with cross sections below 1 mm^2. In: Proc The Int Workshop on Mechano Electromagnetic Property of Com posite Superconductors, September 24, 2001, Kobe, Japan. p. 41 8.
[102] ASTM E 8 89. Standard test methods of tension testing of metallic materials. Philadelphia: ASTM; 1989.
[103] DIN ISO 15579. Zugversuch bei tiefen Temperaturen, DIN Deutsches Institute fuer Normung e. V. Berlin.
[104] IEC 61788 6. Mechanical properties measurement room tem perature tensile test of Cu/Nb Ti composite superconductors. IEC 90/63/CDV, IEC 90/63A/CDV, 1999.
[105] ISO/TC 164/SC 1. Metallic materials tensile testing in liquid helium. Report of ISO/TC 164/SC1, 2000, Berlin.
[106] ASTM E 111 82. Standard test method for Young's modulus, tangent modulus, and chord modulus. Philadelphia: ASTM; 1996.
[107] ASTM E 813 81. A standard test for J_{IC}, a measure of fracture toughness. Annual book of ASTM standards, 1981. p. 1 19.
[108] Krauth H, Nyilas A. Fracture toughness of nitrogen strength ened austenitic steels at 4 K. In: Radon JC, editor. Fracture and fatigue in ECF 3. Oxford: Pergamon Press; 1980. p. 119 28.
[109] Ishio K, Nakajima H, Nunoya Y, Miura Y, Kawasaki T, Tsuji H. Trail fabrication of heavy base metals and welded joints for ITER TF coil. In: Balachandran UB et al., editors. Advances in cryogenic engineering (materials), 44A. New York: Plenum; 1998. p. 73 80.
[110] Nyilas A, Obst B, Zhang J, Muster WJ. Cryogenic tensile, fracture and fatigue investigations of nitrogen alloyed stainless steels. In: 2nd Int Conf on high nitrogen steels "HNS 90", Aachen, Germany, October 1990. p. 191 6.
[111] Nyilas A, Obst B. A new test method for characterizing low temperature structural materials. Advances in Cryogenic Engi neering (Materials) 1996;42:353.
[112] Nyilas A, Obst B, Nishimura A. Fracture mechanics investiga tions at 7 K of structural materials with EDM notched round and double edged bars. In: Balachandran UB et al., editors. Advances in cryogenic engineering (materials), 44A. New York: Plenum; 1998. p. 153 60.
[113] Nyilas A, Nishimura A, Obst B. Further aspects on J evaluation demonstrated with EDM notched round bars and double edged plates between 300 and 7 K. In: Advances in cryogenic engineering (materials), Madison, USA, July 2001.
[114] Nyilas A, Krauth H, Metzner M, Munz D. Fatigue response of materials used in large superconducting magnets for fusion technology. In: Proc of 2nd International Conference on Fatigue and Fatigue Thresholds Birmingham.Beevers CJ, editor. Fatigue 84, vol. III. 1984. p. 1637 49.
[115] Nyilas A. Final Report on ITER coil casing and intercoil structures, Forschungszentrum Karlsruhe. Technical Reports FZKA 6527, November 2000.
[116] Miri AM, Meinecke C, Riegel NA, Ulbricht A, Fink S. Influence of the radial plates on the transient oscillations in the ITER toroidal field model coil using a finite element approach. Trans Appl Supercond 2000;10:596 9.
[117] Lehmann W. FZK experiences of cooling large s.c. systems. In: Proc Symp on Cryogenis Systems for Large Scale Superconduct ing Applications. Toki, Japan: Toki and NIFS; 1996. p. 20 4.
[118] Spath FK et al. Performance tests down to 3.3 K. In: Advances in cryogenic engineering, vol. 39. Plenum Press; 1994. p. 563 70.
[119] Krafft G et al. Forced flow cooling with single phase helium. In: Proceeding of IRR Workshop, Saclay 1981. p. 33 42.
[120] Lehmann W. Considerations on and experience with helium forced flow cooling techniques for superconducting fusion mag nets. In: Proc Cryogenics and Refrigeration Conf Hangzhou. Int. Academic Publishers Pergamon; 1989. p. 319 27.
[121] Cheng X, Lehmann W. Investigations concerning the stability of supercritical helium forced flow cooling in secondary circuits with cold helium pumps. Adv Cryog Eng 1994;39:1723 31.
[122] Lehmann W, Minges J. Operating experience with a high capacity helium pump under supercritical conditions. Adv Cryog Eng 1984;29:813 20.
[123] Hubener J et al. A one cylinder piston pump for high capacity forced flow cooling with supercritical helium. In: Proc. ICEC 10, Helsinki, Butterworth, 1984. p. 574 77.
[124] Zahn G et al. Test of three different pumps for circulating He I and He II. In: Proc. ICEC 14 Kiev, 1992. p. 100 3.
[125] Katheder H, Sußer M. Results of flow experiments with 2 phase helium for cooling of superconductors. In: Proc. ICEC 12 Southampton, 1988. p. 207 11.

[126] Lahn H et al. Cryogenics for the HOMERII high field magnet test facility at the Forschungszentrum Karlsruhe. In: CEC ICMC 2001, Madison, WI, USA.
[127] UK Patent GB 2286450 B, NMR magnet system with s.c. coil in a helium bath.
[128] Lehmann W. Superisolation Deren Qualitat und Degradierung bei Anwendungen in der Kryotechnik. DKV Tagungsbericht Bremen, 2000. p. 99 116.
[129] Lehmann W et al. Experimental results with superinsulated cryogenic transfer line test modules in THISTA. In: Proc. ICEC 16, 1997, Part 1. p. 489 92.
[130] Lehmann W, Zahn G. Safety aspects for LHe cryostats and LHe transport containers. In: Proc. ICEC 7, London, 1978. p. 569 79.
[131] Lehmann W. Sicherheitstechnische Aspekte bei Auslegung und Betrieb von LHe badgekuhlten Supraleiter Magnetkryostaten. DKV Tagungsbericht Heidelberg, 1990. p. 1 17.
[132] Sußer M. Der Kohle Keramik TVO Temperatursensor. DKV Tagung, Ulm, 2001.
[133] Sußer M, Jitschin W. Investigation of the discharge coeffi cient of small venturi tubes. In: Proc. ICEC 18, Mumbai, India, 2000. p. 651 4.
[134] Demattio H, Rusch KD, Sußer M. Automatically controlled low temperature sensor calibration facility. Cryogenics 1994;34(ICEC Suppl):409 12.
[135] Perinic G. The cryogenic control network at the Forschungszen trum Karlsruhe. In: Proc. ICEC 17, Bournemouth, UK, 1998. p. 855 8.
[136] Hofmann A. Design of a fountain effect pump for operating the EURATOM LCT Coil with forced flow of Helium II. Adv Cryog Eng, Part A 1992;37:139 46.
[137] Kraemer HP. Heat transfer to forced flow helium II. In: Proc. ICEC 12, Butterworths 1988. 299pp.
[138] Hofmann A, Pan H, Oellrich L. GM type two stage pulse tube cooler with high efficiency. In: Ross RG ,editor. Cryo coolers, vol. 11. Kluwer Academic/Plenum Publishers; 2001. p. 221 7.
[139] Day Chr, Haas H, Mack A. Development of the cryovacuum pump system for ITER FEAT. In: Jahrestagung Kerntechnik 2001, Dresden, May 15 17, 2001. p. 603 6.
[140] Day Chr, Haas H, Mack A, Murdoch DK. New operational aspects of the ITER FEAT primary vacuum pumping system. Fusion Eng Des, Part B 2001;58 59:301 6.
[141] Mack A, Day Chr, Haas H, Murdoch DK, Boissin JC, Schummer P. First operation experiences with ITER FEAT model pump. Fusion Eng Des, Part B 2001;58 59:365 9.
[142] Murdoch DK, Mack A, Day Chr, Haas H, Boissin JC, Viniar I, et al. ITER FEAT vacuum pumping and fuelling R&D pro grammes. In: 18th IAEA Fusion Energy Conf, Sorrento, I, October 4 10, 2000.
[143] Haas H, Day Chr, Mack A, Methe S, Boissin JC, Schummer P, et al. Test facility TIMO for testing the ITER model cryopump. In: Fusion Energy 1998: 17th Conf Proc, Yokohama, Japan, October 18 24, 1998. p. 1077 80.
[144] Day Chr, Mack A, Murdoch D, Rohrig D. The experimental basis for the ITER cryopump regeneration concept. In: Beau mont B, editor. Proc of the 20th SOFT, Marseille, France, September 7 11, vol. 2. 1998. p. 921 4.
[145] Mack A, Boissin JC, Cohu A, Day Chr, Diegele E, Haas H, et al. ITER primary vacuum pump. In: Beaumont B, editor. Proc of the 20th SOFT, Marseille, France, September 7 11, vol. 2. 1998. p. 1037 40.
[146] European Committee of Manufactures of Compressors, Vacuum Pumps and Pneumatic Tools, British Compressed Air Society, London, UK.