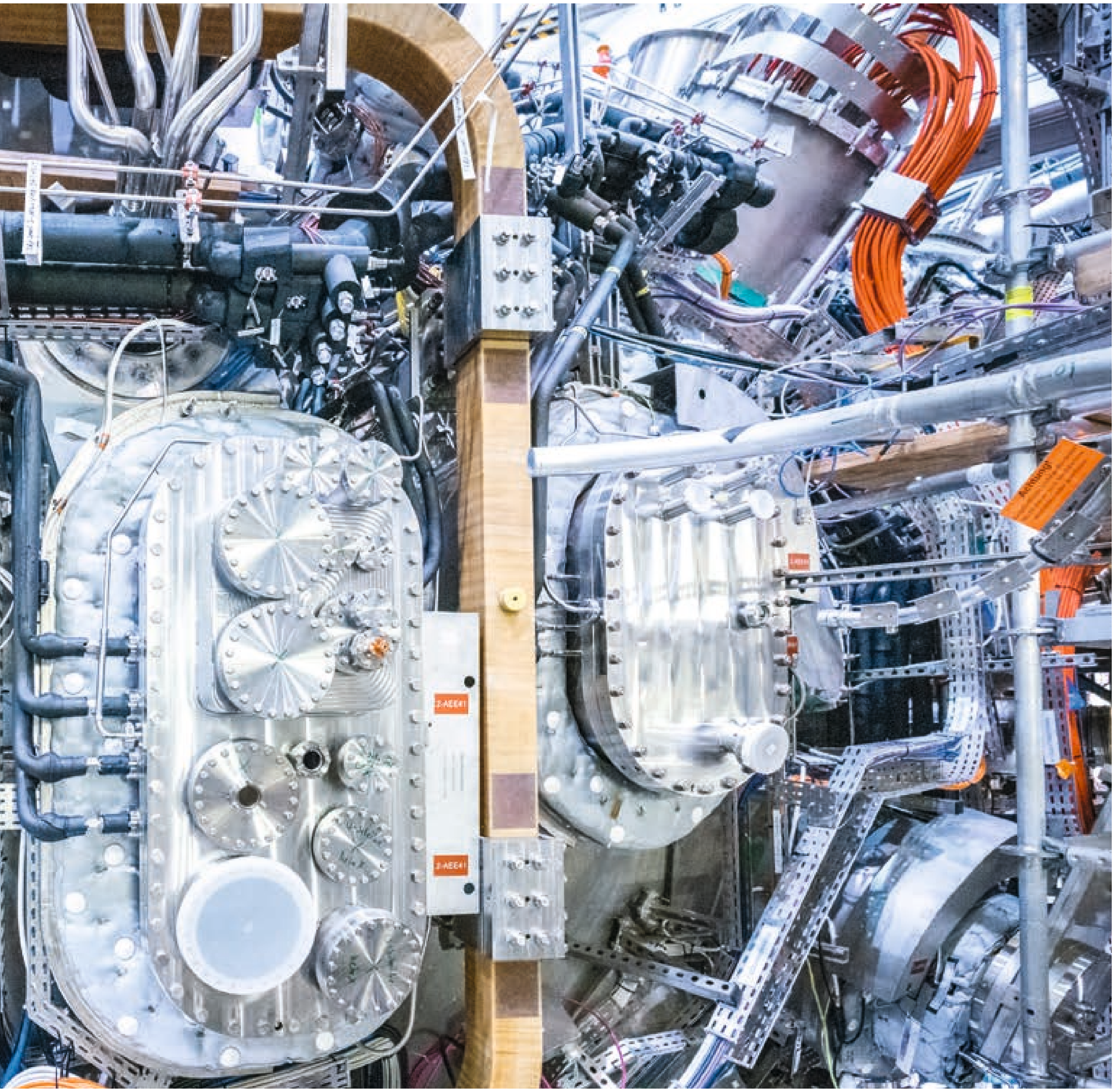
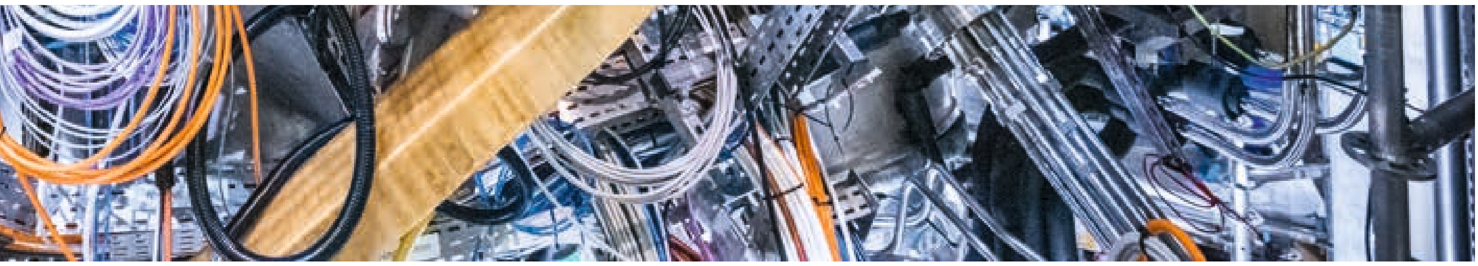


Industry collaborations in fusion

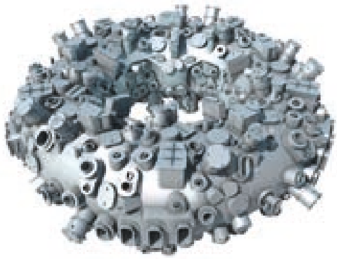


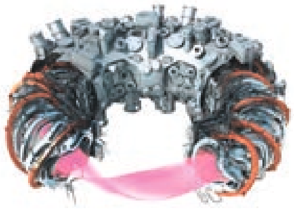
JÜLICH Forschungszentrum

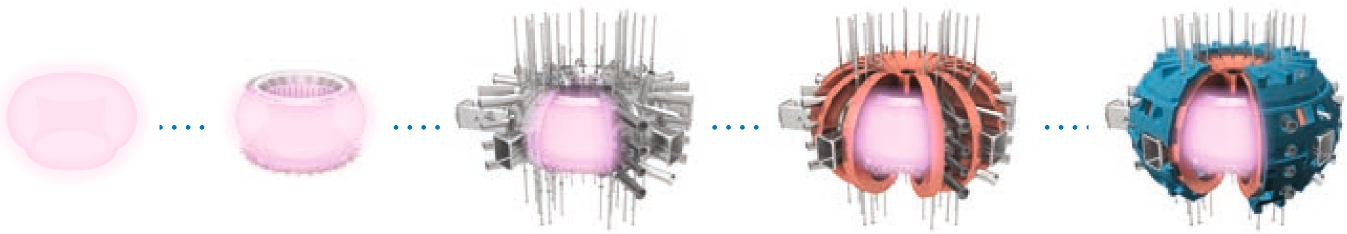
KIT Karlsruher Institut für Technologie

MAX PLANCK INSTITUTE FOR PLASMA PHYSICS

Wendelstein 7-X



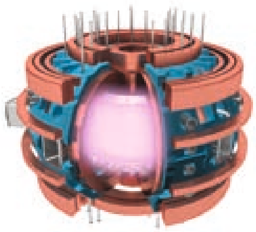




At the cutting edge of technology

How can industrial companies benefit from fusion research contracts?

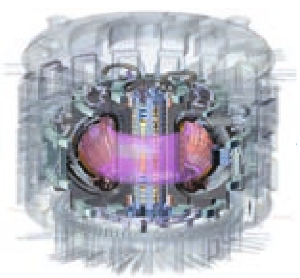
In a world where population is continuously growing and where the standard of living is improving, we are facing global challenges that will most certainly have an impact on many areas of life. One of these challenges is the increasing demand for energy. Most studies indicate that electricity consumption will have increased up to six times by 2100. Moreover, the energy supply should be safe, abundant, affordable, clean and sustainable. Fusion power plants have the potential to make a significant contribution to this, alongside renewables, in the second half of the century.



ASDEX Upgrade

Worldwide fusion research aims at a power plant that generates energy from the fusion of light atomic nuclei. For this, the fuel – an electrically charged hydrogen gas called plasma – has to be confined in a magnetic field cage and requires heating to temperatures above 100 million degrees Celsius. Moreover, the reaction must run continuously in a stable manner.

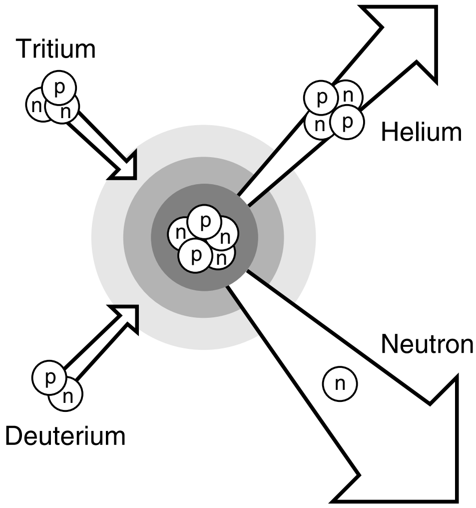
Germany has a leading international position in fusion research and technology. The Max Planck Institute for Plasma Physics in Garching and Greifswald (IPP) and the Helmholtz Centres Karlsruhe Institute of Technology (KIT) and Forschungszentrum Jülich collaborate on the developments towards the realisation of a fusion power plant. All activities are part of a coordinated and cooperative programme, and are embedded in the European fusion programme.



ITER

Industry supplies the majority of the scientific equipment used at the three centres. However, many components simply cannot be ordered from a catalogue. Industrial partners have to develop them first. Often, the required high-tech equipment is on the edge of what is technically feasible. This pushes the companies to technological excellence and contributes to the training of personnel in industry. In addition, the knowledge gained often improves the performance of the industrial partners in their core business or even opens up new lines of business for the companies.

The examples collected for this brochure from IPP, KIT and Forschungszentrum Jülich show that the companies not only benefit directly from the contracts from fusion research but can also increase their competitiveness through the new expertise they acquire.



In a power plant, the neutrons produced during the fusion of deuterium and tritium impinge on the blanket surrounding the plasma vessel. The fast neutrons are decelerated in the blanket material, thus heating it. This thermal energy is then converted to electric energy by means of coolants, heat exchangers, and turbogenerators.

ASDEX Upgrade

Photo: IPP, Bernhard Ludewig

A European strategy for fusion

Fusion is the power source of our sun and the stars, where hydrogen nuclei fuse under the extreme pressure of gravity. Under terrestrial conditions, it is the two hydrogen isotopes deuterium and tritium which fuse most easily, creating a helium nucleus and a neutron as well as large amounts of usable energy. One gram of fuel can generate as much energy in a fusion power plant as the combustion of 11 tonnes of coal.

The European fusion research institutions are organised in the EUROfusion consortium, where the scientific programme is based on a roadmap that describes the research and development work required to create the basis for an electricity-generating fusion power plant in the second half of the century.

In Europe, the path to a fusion power plant focuses on two concepts, the tokamak and the stellarator, which seek to confine plasmas using magnetic fields sufficiently well to reach temperatures of more than 100 million degrees Celsius.

The most important research infrastructure on the way to a fusion power plant is ITER. This facility of the tokamak type is being built in the south of France in an international cooperation and is intended to demonstrate the scientific and technological feasibility of nuclear fusion on Earth. At ITER, the fusion of deuterium and tritium will produce a fusion power of up to 500 million watts for 400 seconds for the first time. In addition to the large fusion facilities JET (UK) and JT-60SA (Japan), small and medium-sized tokamaks – including ASDEX Upgrade at IPP Garching – play an important role in addressing specific issues for the development and operation of ITER.

In the European roadmap, the stellarator line represents a long-term alternative or backup strategy for the tokamak. Wendelstein 7-X – at IPP Greifswald – is the world‘s largest stellarator-type facility. Its task is to investigate the power plant suitability of this type of construction. In addition, Wendelstein 7-X will also contribute to the development of the physics and technology of ITER.

In parallel with ITER construction, concept development of the European demonstration fusion power plant DEMO is already underway. High-power operation at ITER will provide important insights for finalising the DEMO design. DEMO is intended to feed hundreds of megawatts generated via fusion into the grid and to operate with a closed fuel cycle.

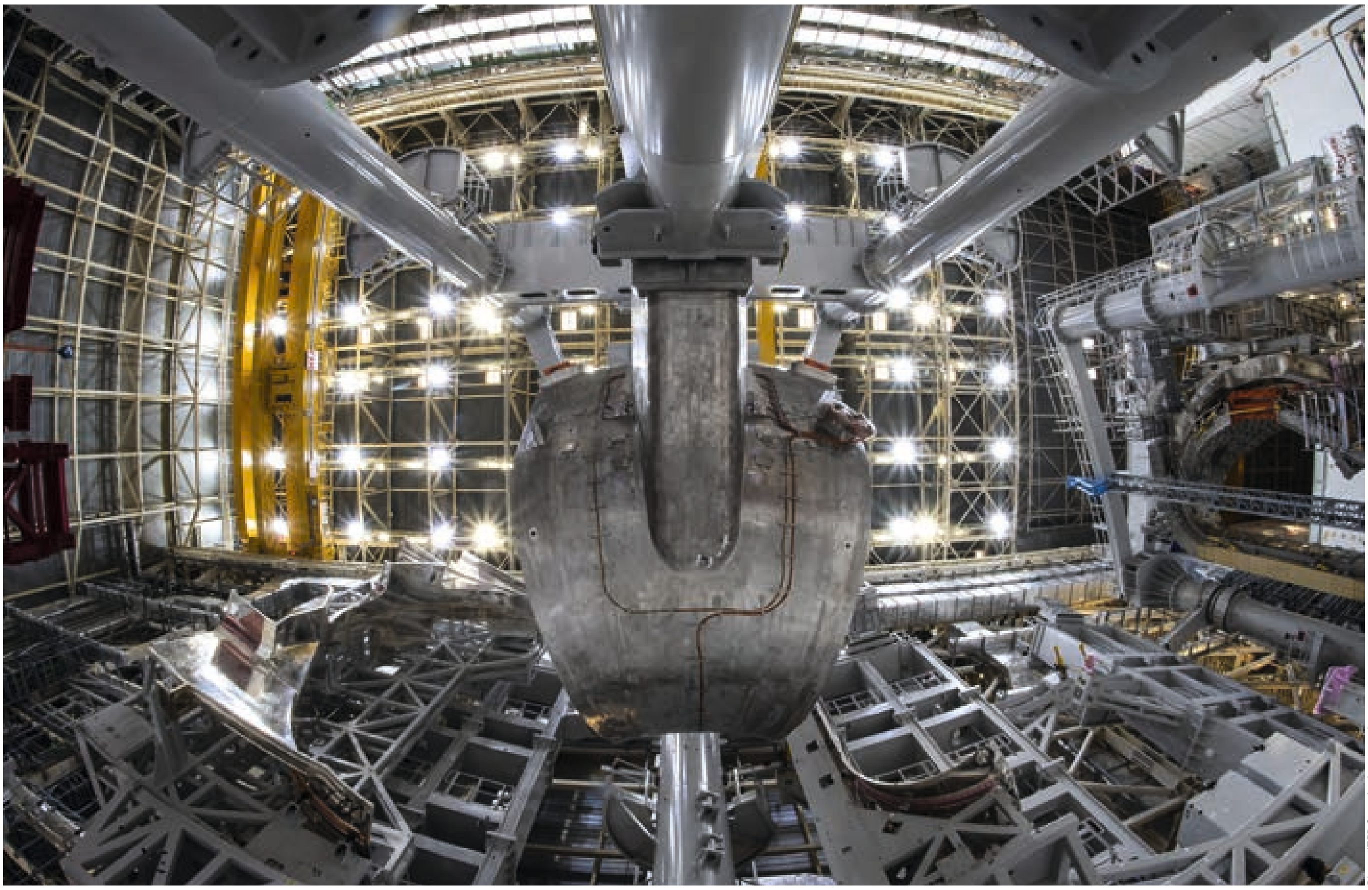
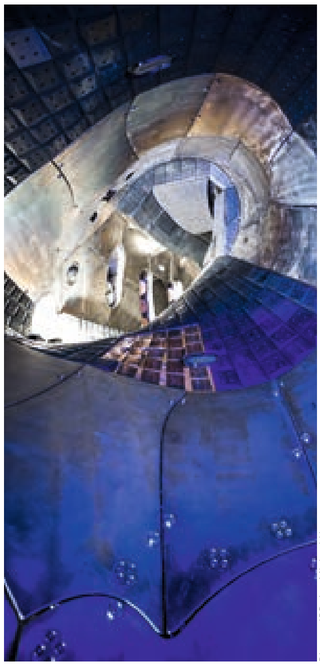


Photo: ITER Organization, www.iter.org

ITER assembly: in the centre of the picture, a 440-tonne sector of the vacuum vessel

Plasma vessel of Wendelstein 7-X



Photos: IPP, Jan Michael Hosan

MAN Energy Solutions SE, Deggendorf, Germany

"The Mona Lisa of the art of welding" * The plasma vessel of the Wendelstein 7-X

*Der Spiegel 1/2009 (a German news magazine)

Photo: IPP, Wolfgang Filser

Welding the Wendelstein 7-X plasma vessel

The plasma vessel for the Wendelstein 7-X fusion experiment, which looks like a wound-up steel tube, is designed to accommodate a hydrogen plasma with a temperature of about 100 million degrees. The almost ring-shaped plasma chamber has an outer diameter of 12.8 meters and a height of 2.5 meters. The steel vessel must match precisely the symmetry of the magnetic field which confines the hot plasma. The requirements placed on the steel vessel construction thus presented completely new challenges for MAN Energy Solutions: it was necessary to manufacture an unusually complex, three-dimensional vessel with a volume of 30 cubic meters made of 17 millimeters thick stainless steel – with a dimensional tolerance of two millimeters (plus/minus)!

Altogether, the plasma chamber consists of 200 stainless steel rings. Each ring is composed of 15 centimeter-wide steel strips, which are bent in several places in order to achieve the required contoured geometry. 20 sectors were fabricated from these rings and delivered to Greifswald were they were welded together onsite using techniques suitable for ultra-high vacuum, resulting in the completed chamber. The plasma vessel wall has roughly 300 ports of different sizes, which are necessary for heating the plasma and investigating it scientifically.

To successfully complete the project, MAN had to introduce a variety of new technologies at its Deggendorf site:

- Before manufacturing such a complex vessel, detailed computer models had to be developed. This prompted MAN Energy Solutions to introduce the most advanced program available for three-dimensional spatial design. Since then, 3D-spatial design has become part of the company's expertise.

- The dimensional accuracy of the vessel had to comply with the highest standards. For checking and verifying the geometry of the vessel MAN Energy Solutions in Deggendorf applied an electronic, laser-assisted surveying system for the first time, which is now routinely used in all production at the company.

As a company, MAN Energy Solutions has benefited both directly or indirectly from these developments in steel construction. New technologies were introduced and improved with the customer, the IPP. MAN has already applied these new procedures for the series production of petrochemical and chemical reactors. The specialists – already highly qualified – were able to increase their expertise and are now assembling the largest stainless steel high-vacuum chamber ever built for the international fusion reactor ITER. With its proven expertise in complex stainless steel processing and innovative welding technology, the company also won the contract for the supply of ports and port stubs for ITER. These ports allow access to the plasma chamber for remote operation and other systems such as diagnostic, heating and vacuum systems.

Photo: ITER

With the assembly of the ITER cryostat - here the "Upper Cylinder" – the Deggendorf company once again demonstrates its know-how in complex stainless steel processing.

Photo: MAN Energy Solutions

Port for the international experimental reactor ITER

▶ The technology used, in particular the assembly of the vessel using single steel strips derived from pre-shaped segments, was extremely innovative but required highly sophisticated welding techniques to prevent distortion. These techniques were put to the test in a spectacular way.

▶ Very precisely positioned steel brackets were necessary for the installation of the wall elements inside the plasma chamber. To achieve the accuracy required in a spatially confined environment, the company acquired a six-axis robotic manipulator that is now used routinely for various applications. Furthermore, the company used three-dimensional water jet cutting technology to precisely manufacture the 300 port openings in the vacuum vessel.

In order to induce superconductivity in the 70 magnetic coils of the Wendelstein 7-X device, liquid helium is used to cool the coils down to -270 degrees Celsius. Once they have reached this state, the coils require almost no power. The plasma vessel, the outer vessel and all 254 connecting pipes, which facilitate access to the machine interior, are shielded by thermal insulation. This consists of a wrinkled, multi-layer plastic foil coated with aluminum, which is in contact with an actively cooled covering. MAN Energy Solutions and IPP together successfully mastered this completely new and extremely complicated engineering problem.

Photo: IPP, Wolfgang Filser

"Have you ever tried to wrap up a hedgehog?" The thermal insulation of the Wendelstein 7-X

Inner and outer view of the Wendelstein 7-X plasma vessel

Here are a few significant features for the manufacturing of the thermal insulation:

▶ Actively cooled cover elements, so-called shields, had to be manufactured for the thermal insulation of the plasma vessel. Due to the unconventional shape of the vessel and the extremely confined working environment, the precisely shaped shields had to be made with very high accuracy. Despite advanced shaping technology, attempts using steel, brass, and copper were unsuccessful. A fiberglass-reinforced plastic shield was the solution.

▶ Not only did the plastic shields have to be formed exactely to the unusual shape ot the vessel, they also had to be suitable for conducting heat. A technology based on laminated copper meshes, which has led to a joint patent, proved to be the solution. The result is a heat-conducting composite that is suitable for use at extremely low temperatures.

▶ Assembly of the thermal insulation by MAN Energy Solutions meant that the company was taking a risk. Unlike the situation at normal construction sites, Wendelstein 7-X represented a complex scientific environment, where the contractor had to react quickly to adjustments and changed requirements. This is typical for a "first of its kind" facility.

Photo: IPP, Beate Kemnitz

The manufacturing contract for the thermal insulation caused MAN Energy Solutions SE to explore a new field of high-tech engineering. With the expert support of a consultant engineer from Linde AG, MAN has familiarized itself with this unknown territory. In addition to fusion devices, cryogenic technology will be applied to high-energy accelerators such as the FAIR project, which is currently being built in Darmstadt.

Photo: IPP, Anja Richter Ullmann

Assembly of the thermal insulation for the outer vessel (brass shields)

Thales Electron Devices S.A., Paris-Velizy, France
Reinhold Mühleisen GmbH, Gerlingen, Germany
Element Six Ltd., London, UK
Diamond Materials GmbH, Freiburg, Germany
Reuter Technologie GmbH, Alzenau/Schöllkrippen, Germany

Efficient microwave heating delivers megawatts of power

Ignition of a fusion reaction requires a system suitable for heating the plasma to 100 million degrees. One option is heating by means of microwaves. Similar to a microwave oven, which everyone is familiar with from the household, high power vacuum tubes are used as microwave sources. In a household microwave, this is the magnetron, which provides an output power of up to one kilowatt operating at a frequency of 2.45 gigahertz. The most powerful vacuum tubes in the world operate in the area of fusion research: at a frequency of 100 to over 200 gigahertz, output powers of at least one million watts (1 megawatt) are generated. The so-called gyrotrons serve this purpose. At Wendelstein 7-X, those tubes deliver their full power of one megawatt for up to 30 minutes.

For the development of those gyrotrons installed at Wendelstein 7-X and manufactured by the company Thales Electron Devices, Thales, the Karlsruhe Institute of Technology (KIT) and IPP are working closely together. A partner in manufacturing of high-precision components is the Reinhold Mühleisen GmbH, which supplies high-precision mode converters and mirror systems for the gyrotrons. The companies Element Six Ltd. and Diamond Materials GmbH deliver the diamond disks of the microwave windows and Reuter Technologie GmbH contributes know-how on soldering technology to join diamond and copper. Already ten gyrotrons are operating at IPP Greifswald. A more powerful gyrotron with up to 1.5 megawatts of output power has been developed. The prototype tube, industrially manufactured by Thales, is tested at KIT and delivered to IPP in 2022.

High-performance microwave tube for continuous operation

Photo: IPP, Wolfgang Filser

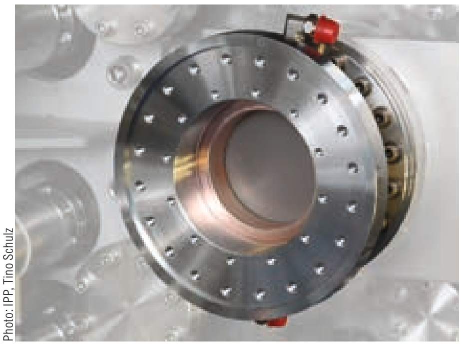


Photo: IPP, Tino Schulz

Soldered diamond window using the CVD process in a diamond window

Thanks to this collaboration between research and industry, meanwhile gyrotrons for other plasma experiments have been developed – directly derived from the design for Wendelstein 7-X. One of those is the dual-frequency gyrotron developed in cooperation between KIT and the Swiss Plasma Center for the Swiss Tokamak à Configuration Variable (TCV). This gyrotron can operate with one megawatt of output power at a frequency of either 84 or 126 gigahertz. Furthermore, the industrial prototype for ITER, which is currently undergoing final testing, was developed in a cooperation between European research institutes and the EU organisation "F4E - Fusion for Energy". The knowledge gained from the development of the tubes for Wendelstein 7-X and ITER will directly go into the design of the gyrotrons for the future DEMO demonstration power plant. Those gyrotrons for DEMO will achieve at least two megawatts of output power at frequencies of over 200 gigahertz.

Photo: IPP, Jan Schölzel

140 metal mirrors transmit the microwaves from up to now ten gyrotrons to the Wendelstein 7-X plasma

Diamond windows to the plasma

A critical component are the windows between the gyrotron tube and the outside world and between the beamline and the plasma. They are made of artificial diamonds with a high level of purity to keep the thermal losses as low as possible. These diamond windows, which have been manufactured by Diamond Materials and Element Six in collaboration with the Karlsruhe Institute of Technology using the chemical vapour deposition (CVD) technique, are unique worldwide and excellently suited for microwave and millimetre-wave heating applications with their diameters of up to 120 millimetres and thicknesses of 1.8 millimetres.

Recent developments of CVD diamond windows focus on the transmission of millimetre waves of different frequencies through a so-called Brewster window. By using different frequencies, it is easier to reach the region where plasma instabilities occur and should be broken up by energy irradiation. Therefore, future fusion facilities will use such multi-frequency gyrotron systems as a standard feature.

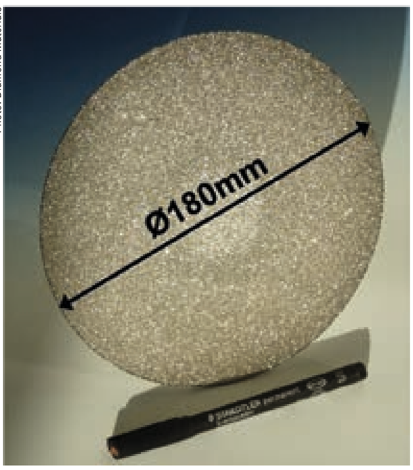
A two-millimetre-thick diamond disk is inclined in a waveguide structure. To avoid reflections of millimetre waves, the inclination of the disk axis is 67.2 degrees: the Brewster angle of diamond. Diamond disks with a diameter of 180 millimetres are required to realise a waveguide diameter of 63.5 millimetres. Such a size has not been available before. The Karlsruhe Institute of Technology, in cooperation with Diamond Materials, mastered the challenge of producing diamond disks of this size with good microwave properties.

The diamond window requires reliable cooling, but a water-based technique risks corrosion. For that reason, silicone oil was successfully used as coolant for the first time. During their longstanding cooperation, Reuter Technologie and the Karlsruhe Institute of Technology have developed their skills in soldering diamond and copper with special copper-silver-titanium solders. Diamond Materials in Freiburg is now also successfully soldering diamond disks into copper structures. This soldering provides the basis for building a diamond window, which, after a further soldering step, is surrounded by a stainless steel housing and built into a standard millimetre wave transmission line. During the manufacture of the diamond windows with integrated cooling, the soldering of the different materials with the simultaneous requirement of high vacuum strength provided a particular challenge.

Currently, work is underway to develop a 1.5-megawatt gyrotron for continuous operation at Wendelstein 7-X and to upgrade the transmission lines for the use of twelve instead of now ten microwave sources. Part of this project to increase the heating power at Wendelstein 7-X is a new industrial contract with Thales Electron Devices for the construction of a 1.5-megawatt prototype source. The design of this gyrotron is based on the successful Wendelstein 7-X gyrotron, which also forms the basis for the European gyrotron for the international experimental reactor ITER.

All these improvements in the concept and the technical details have opened up new ways for manufacturing high-power microwave tubes required in communications technology, materials technology, the International Thermonuclear Experimental Reactor (ITER) fusion experiment and the first fusion power plant, “DEMO”. Thales Electron Devices, as the primary contractor, has gained extensive knowledge through the execution of these contracts and is now significantly better positioned in the market. With the acquired expertise, Diamond Materials and Reuter Technologie have also clearly improved their position for winning future contracts.

Photo: Diamond Materials



CVD diamond disk from Diamond Materials GmbH with a diameter of 180 mm

Plansee SE, Reutte, Austria

Heating fusion plasmas to temperatures of roughly 100 million degrees Celsius requires very high power outputs in the range of ten million watts. Although the heated plasma inside the vessel will be confined by the magnetic field, contact between the plasma boundary and the wall segments cannot be avoided. The temperature of the plasma decreases dramatically from its center to its outer boundary where it is "only" about 100,000 degrees Celsius. To protect the wall of the plasma vessel from damage, the huge heat flow from the plasma has to be conducted through the wall. The sections of the wall are protected by water-cooled wall elements. The high-performance heat exchangers are known as "divertors".

Wendelstein 7-X is to demonstrate that stellarators are capable of continuous operation. This requires a powerful divertor. Plansee SE designed so called "target elements" for the divertors, which must be continuously capable of withstanding ten megawatts per square meter. A sophisticated combination of carbon-fibre-reinforced carbon and water-cooled metal blocks, also known as heat sinks, had to be developed. Significant steps in this development were made in close collaboration with IPP:

10,000 hotplates on one square meter The high load Wendelstein 7-X wall

High-performance water-cooled wall elements

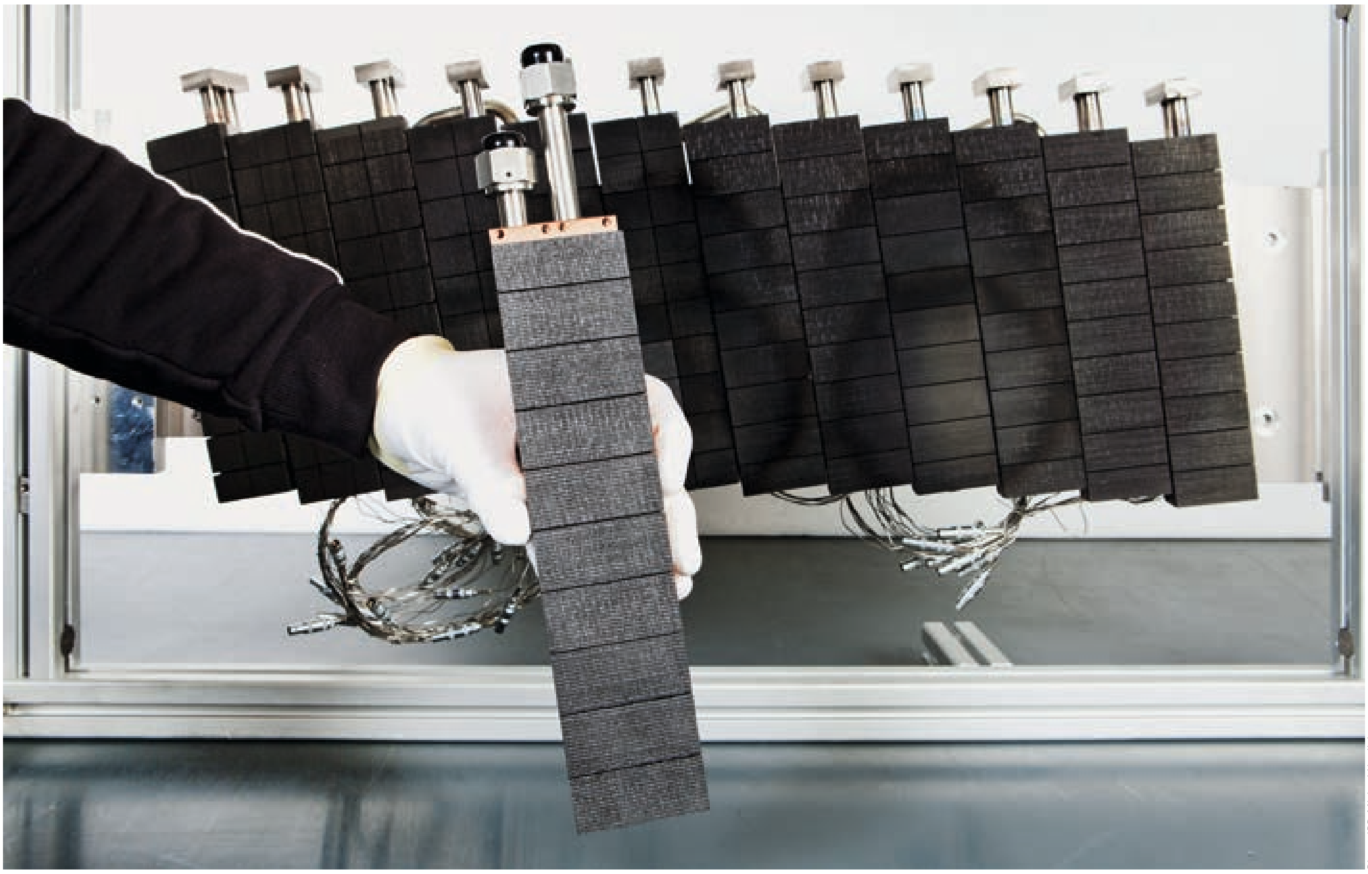


Photo: IPP, Michael Herdlein

▶ Joining the carbon-fibre-reinforced carbon to the water-cooled heat sink made of a metal alloy turned out to be extraordinarily demanding. The carbon is in contact with the plasma and exposed to an extremely high heat load; pressurized cooling water circulates through the heat sink. For joining the two elements, the carbon had to be coated with a structured copper layer and then welded onto the heat sink to ensure good thermal conductivity from the surface of the carbon layer to the heat sink. At the same time, it was necessary to compensate for the different thermal expansion coefficients of the two materials. Plansee patented the procedure.

▶ The water-cooled heat sinks must dissipate tremendous quantities of heat under conditions of continuous operation. The pressurized cooling water must be circulated through the body of the metal heat sink. For this purpose, the cooling channel had to be designed such that turbulent flow occurs and more heat is dissipated.

▶ Quality assurance for this complex structural element composed of several materials presented a huge challenge for the production of altogether 890 elements, representing 18,000 tiles. IPP, together with its contractor Plansee, developed a quality assurance plan based on both systematic and randomized high-performance tests.

Because standard procedures were not available for non-destructive checking of joints, the company developed special test methods on the basis of ultrasonic, X-ray, and thermographic testing.

The heat load of ten million watts per square metre – this means that the wall of Wendelstein 7-X is exposed to higher loads than that placed on the edges of the wing of the space shuttle when it re-entered the atmosphere (six million watts per square metre, which, however, "only" occurred for several hundred seconds in that case). Carbon-fibre-reinforced carbon tiles were also used in that application. Space technology and fusion technology had been combined for the development of materials exposed to high temperatures. Under the management of the IPP, an important joint European project promoted by the EU under the name EXTREMAT had been carried out. Plansee played a leading role among the 30 project partners, which are predominantly from the industrial sector.

Target elements during thermographic testing

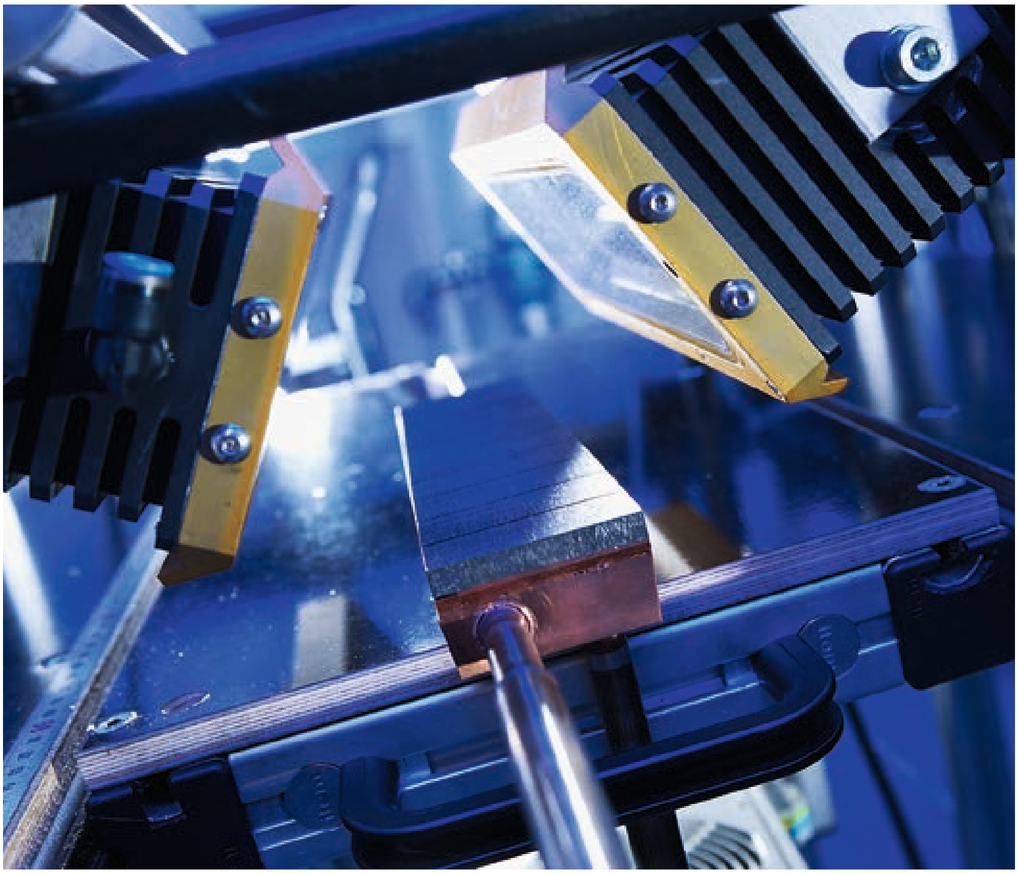


Photo: Plansee SE

Using a technology that was introduced for the French fusion experiment, Tore Supra (meanwhile WEST), Plansee and IPP refined it for Wendelstein 7-X and improved its quality and reliability. These heat-conducting carbon-fibre-reinforced carbon-metal composites are certain to find a wide range of applications.

Bilfinger Noell GmbH, Würzburg, Germany
ASG Superconductors SpA, Genoa, Italy

"Nature determined the form for us." The superconducting magnetic coils for Wendelstein 7-X

The plasma being studied at Wendelstein 7-X is 100 million degrees hot. Ring-shaped, twisted magnetic fields confine the plasma and thermally isolate it from the cold vessel walls. In stellarator-type fusion devices the magnetic field is determined exclusively by the geometry of the outer magnetic coils. For more than ten years, scientists had searched for the ideal magnetic field cage using a supercomputer. Their calculations became reality in the bizarre coil windings. The technical realization of the coil geometry was extremely challenging for Bilfinger Noell GmbH. It set up a consortium and a European network involving many sub-contractors and solved numerous engineering problems:

The consortium partners Bilfinger Noell GmbH and ASG Superconductors SpA developed methods to bring the superconductor into the spatially complex shape. Suitable winding moulds were built and successfully introduced. Bilfinger Noell acquired valuable experience in the design of the steel casings and their manufacture using an optimized casting process, the embedding of the winding packages in the steel casings and their high-precision mechanical machining.

In the event of an emergency shutdown, the coils have to withstand very high voltages and must be extremely robust. Each individual coil was therefore subjected to various tests with voltages of up to 13,000 volts. One particularly sensitive high-voltage test, which IPP developed with Bilfinger Noell specifically for the factory test, was conducted in a dilute gas atmosphere. Deficiencies in the electrical insulation of the coils caused visible discharges, which could then be rapidly located and repaired. This – extraordinarily strict – "Paschen test" set new standards for the quality assurance of superconducting magnets.

The team of Bilfinger Noell GmbH has developed remarkable expertise in the completion of this contract. This competence has since been used successfully for other projects, for example at ITER US for the Paschen test facility. The GSI Helmholtz Center for Heavy Ion Research awarded the company a contract for the production of superconducting magnets for the international particle accelerator FAIR in Darmstadt. ASG Superconductors used the experience gained with the Wendelstein 7-X coils in a consortium that applied for the manufacturing of the ITER toroidal field coils and is now fabricating the EU winding packages for the international test reactor.

Photo: IPP, André Künzelmann

◄ **Manufacturing of non-planar coils for Wendelstein 7-X**
▼ **Non-planar coil – here during “coil threading”**

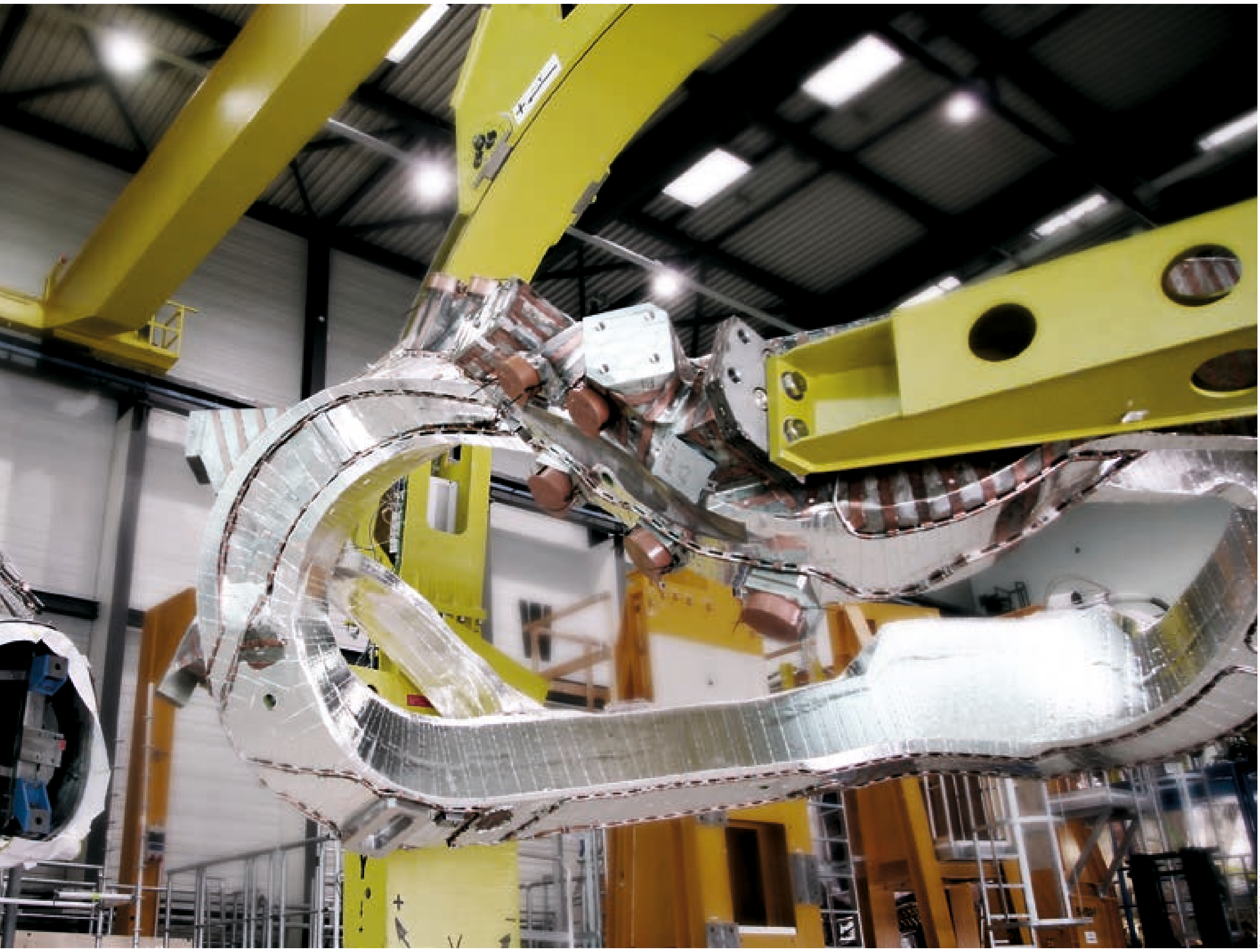


Photo: IPP, Anja Richter

Linde Kryotechnik AG, Pfungen, Switzerland
Linde Engineering, Munich, Germany

The Wendelstein 7-X magnets must be cooled to -270 degrees Celsius. Conventional superconductivity begins at that temperature, which is less than four degrees above absolute zero. To accomplish this, liquid helium is pumped into the space between the wires of the coils. A large refrigeration plant liquefies the helium gas and cools it to the required low temperature. Since the liquid helium is fed into a closed-loop cooling system, the system must be able to react with exceptional flexibility to the various operational states of the magnets.

Linde Kryotechnik developed a special refrigeration system for Wendelstein 7-X based on industrially available technology. Linde managed to meet the extraordinarily high demands on the flexibility of the cryogenic system by the adroit combination of turbines, cooling compressors and cold circulators. A storage tank for the liquid helium makes rapid increases in performance possible. The helium refrigeration system of Wendelstein 7-X is one of the most modern and flexible systems worldwide.

Through the construction of the highly specialized, highly flexible and precise Wendelstein 7-X refrigeration system, Linde Kryotechnik was able to develop its expertise in the design of complex large-scale refrigeration systems and thus to further qualify itself for new, major projects. Linde Kryotechnik supplies the cryogenic helium distribution system for the international experimental reactor ITER in southern France. Linde know-how is also being relied on in the south of Sweden, where, starting from 2023, the European Spallation Source ESS is to supply neutrons with the worldwide highest intensity.

Close to absolute zero
Refrigeration system for Wendelstein 7-X

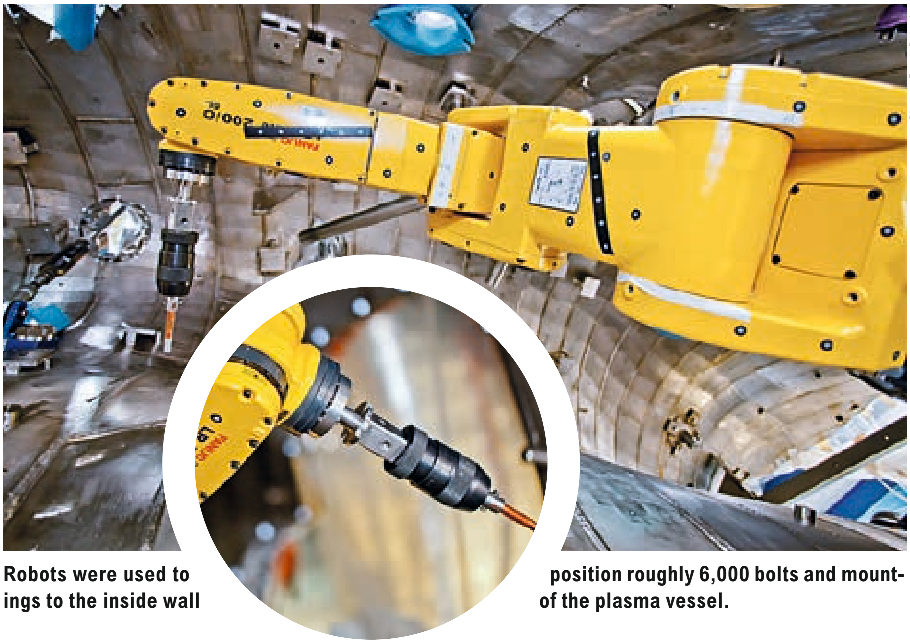
Cold, colder, Wendelstein 7-X – view into the refrigeration system

Photos: Linde Kryotechnik AG

“Six tons positioned with clockwork precision” Development of special tools and systems for assembly

RST Rostock System-Technik GmbH, Germany

Assembly equipment, which allows alignment for all six degrees of freedom, was necessary for mounting the coils, ports, and in-vessel components of Wendelstein 7-X. Tight spatial requirements restricted the operation of assembly equipment and extremely precise specifications had to be taken into consideration. RST manufactured two manipulators straddling the machine that could be rotated and positioned precisely for the positioning and alignment of the coils (up to 3.5 meters high and six tons in weight), as well as a manipulator for the high-precision positioning of installed components in the restricted space of the plasma vessel using computer control systems. Several other systems capable of holding components weighing up to 70 kilograms and positioning them with millimeter precision in the curved plasma vessel are used for the step-by-step upgrading of Wendelstein 7-X. Since the vessel is now equipped with graphite wall tiles and physical measuring instruments, and since the assembly staff need enough space to work within the vessel, a minimum size is high priority for the assembly systems.



Photos: Fanuc Robotics

Robots were used to position roughly 6,000 bolts and mountings to the inside wall of the plasma vessel.

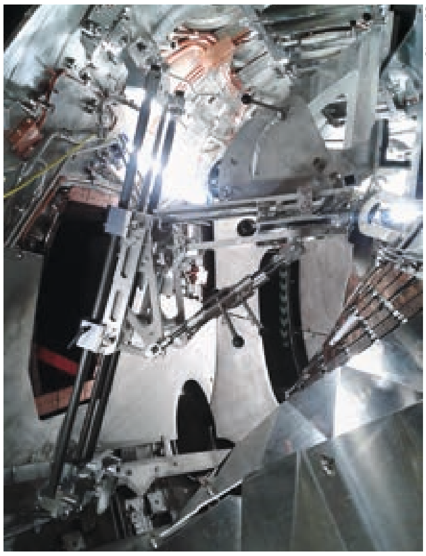


Photo: IPP

Positioning device for the upgrading of Wendelstein 7-X, underway since 2018

RST has developed a complex manipulation technology for IPP that makes the optimal use of the available space. These handling systems are practical, stable and achieve a precision of up to 0.5 millimeters. The contracts have furthered significantly the construction and manufacturing expertise of the company, which enables it to become more competitive in a specialized field. RST has acquired detailed know-how on the positioning and controlling of various pieces of precision equipment, which can be used economically even where access and direct observation are restricted. The acquired expertise can be applied across all industries. The aerospace industry was inspired by RST to adopt pragmatic-technical handling concepts, which were first used at IPP, and integrated them into their own systems. In subsequent projects, IPP has also benefited from solutions transferred from RST.

Photo: TÜV Rheinland

Wendelstein 7-X

TÜV Rheinland AG, Cologne, Germany

Without compromises Nuclear fusion and radiation protection

If you type "safety and nuclear fusion" or "radiation protection and nuclear fusion" into a search engine, you will quickly notice links to Greifswald, or, to be more precise, links to Wendelstein 7-X. And there is good reason for this: fusion is not only a future topic in research, but also in the field of safety and radiation protection.

In the technical regulations for radiation protection and nuclear technology, there are no special rules for fusion plants, whose safety characteristics differ significantly from fission power plants. Therefore, it is not possible to use an established, directly applicable set of rules for evaluating the Wendelstein 7-X safety concept. This was particularly challenging as the experimental facility has a highly complex, non-static structure from the safety and radiation protection perspective, and specific fusion aspects must be taken into account. The operation conditions of the facility range from simple hydrogen plasmas of low density and short duration without necessity of radiation protection, to long-lasting, dense deuterium plasma pulses with the generation of ionising radiation and, to a very small extent, radioactive tritium.

Safety and radiation tests ensure the protection of people and the environment from the harmful effects of ionising radiation.

TÜV Rheinland has gained a unique insight into the current development of fusion research by applying its comprehensive and long-standing experience with research reactors, large-scale accelerator facilities, and nuclear power plants. This knowledge will also play a role in the safe operation of ITER, where TÜV Rheinland has already been able to use its experience from the commissioning of Wendelstein 7-X.

TÜV Rheinland, one of the world's leading independent testing service providers, has a wealth of experience in various applications of ionising radiation in research, medicine, technology, and energy generation. This experience allowed TÜV Rheinland to derive safety and radiation protection requirements applicable to Wendelstein 7-X. The focus was particularly on monitoring and controlling the neutrons and tritium generated by fusion reactions.

In a multiphase process, a review was carried out to determine which boundary conditions must be fulfilled to ensure safety and radiation protection and whether the technical, organizational, and personnel measures required for this are either already in place or can be implemented punctually prior to the relevant operation phase. This resulted in a process of successive safety reviews which ensures state-of-the-art radiation protection science and technology requirements for a dynamically developing experimental facility at all times.

Ulba Metallurgical Plant JSC, Ust-Kamenogorsk, Kazakhstan

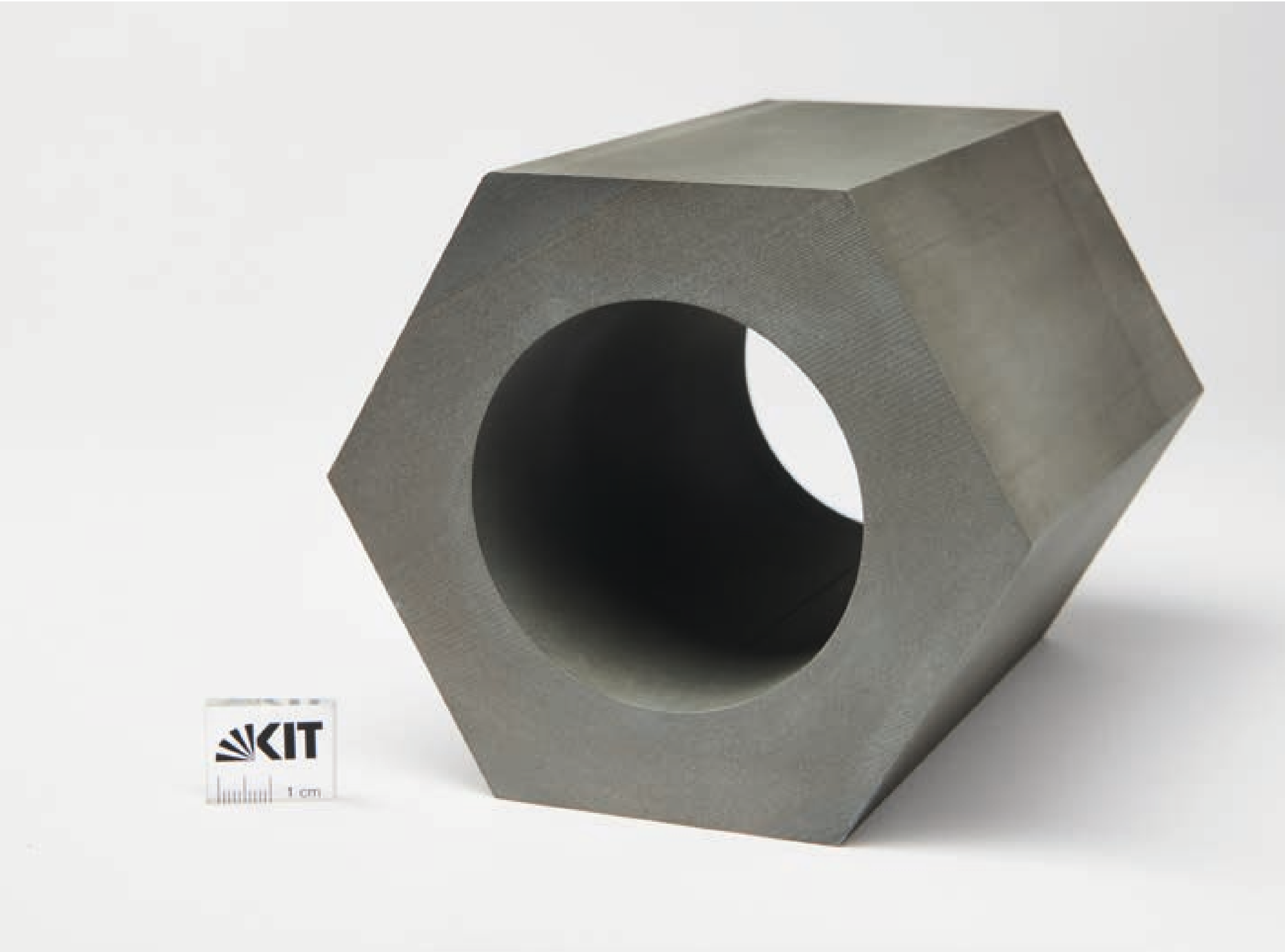


Photo: KIT

Hexagonal TiBe12 block after final machining

Closing the loop
Neutron multiplier for tritium production in the DEMO demonstration power plant

In a future fusion power plant, the so-called blanket will cover the inner wall of the plasma vessel. Fast neutrons produced by the fusion reaction release their energy in it in the form of heat. In addition, neutrons produce tritium, the fuel needed for fusion, by interacting with the lithium contained in the blanket. Not all neutrons reach the zone with the lithium, so materials that act as neutron multipliers are therefore in demand.

Until now, pure beryllium was considered the most suitable solid material for neutron multipliers to generate the amount of tritium needed to close the fuel cycle. The previous reference concept, the helium-cooled solid blanket module for tritium production for the ITER experimental fusion reactor, was based on alternating layers of lithium ceramic and beryllium beads. However, irradiation tests show that at temperatures below 500 degrees Celsius, almost all of the tritium produced remains in the beryllium. However, the operating temperature of a beryllium packed bed should not exceed 650 degrees Celsius, because otherwise the beryllium would swell too much meaning the end for this concept.

Since 2004, a team at the Karlsruhe Institute of Technology (KIT) has been developing advanced materials for neutron multipliers based on intermetallic beryllium alloys. This class of materials is characterized by lower tritium retention and swelling combined with higher melting temperatures - key advantages for the tritium-breeding blanket design. They allowed crucial conceptual changes to the solid-state blanket module: Lithium-containing ceramic pebbles confined by solid hexagonal blocks made of titanium beryllide. This innovative design is currently favored as the new reference concept for the helium-cooled solid blanket of the European demonstration power plant DEMO, the ITER successor.

An important step towards this goal was the development of an industrial manufacturing technology for hexagonal blocks from titanium beryllide. For this purpose, KIT closely cooperated with Ulba Metallurgical Plant. The KIT team of experts experienced in the development of beryllides provided the geometry and material specifications as well as the limits for the most important technological parameters. Finally, for the industrial production of beryllium-containing products, the powder metallurgical manufacturing route proved to be the optimal one: first, the material was treated with hot isostatic pressing (HIP) for five hours at 1150 degrees Celsius under argon pressure of 1320 bar to produce titanium beryllide powder. The compressed beryllide was then ground into powder and re-solidified, this time by vacuum hot pressing. The latter method was found not to produce any cracks, unlike the HIP ingots.

As a result of this development, Ulba Metallurgical Plant JSC is now able to produce complex shapes from beryllides. As early as the 1960s, such materials were being investigated as potential high-temperature materials for space travel and aircraft. However, because of the complicated manufacturing process, other compounds were selected at that time. Today's optimization of this manufacturing technology, combined with a considerable reduction in price, could lead to the emergence of a new market for these materials. This is particularly true for applications where brittleness can be compensated for by exceptional strength. The team of experts at Ulba Metallurgical Plant is proud to have solved this important technological problem together with KIT. Developing new products at the customer's request - the company was able to show what potential it has here.

Beryllides are very hard and brittle materials. To finish the outer hexagonal shape and cut the inner hole, the company used wire electroerosion and waterjet cutting methods. Together with KIT, they succeeded for the first time in industrial fabrication of blocks from titanium beryllide reaching a size of 144 × 150 square millimeters and whose density achieves 98.8 percent of the theoretical one.

The fabrication of several blocks of titanium and chromium beryllides demonstrates the good replicability of this novel approach. This development paves the way for a full-scale prototype model as well as its qualification and functional testing under the conditions expected for the DEMO fusion reactor's helium-cooled solid blanket.

The innovative HTS-CroCo technology opens up new possibilities for future fusion reactors. In addition, this new development also offers opportunities to minimize losses during the transport of high currents. The simple manufacturing process of the HTS-CroCos is designed for industrial production in long lengths. Parallel use (stranding) of several HTS-CroCos allows currents of well over 100,000 amperes. The company Vision Electric Super Conductors GmbH will use this technology, for example, in electrolysis plants, drastically reducing the losses that would otherwise occur and reducing the space allocation. In addition, the loss-free transport of high direct currents over long distances in slim, underground routes is also possible.

Some like it cold
HTS-CroCo - base for future, compact and efficient cables in network expansion

Design of a cable with HTS CroCo conductors for a power of two GW at voltages of ±50 kVDC

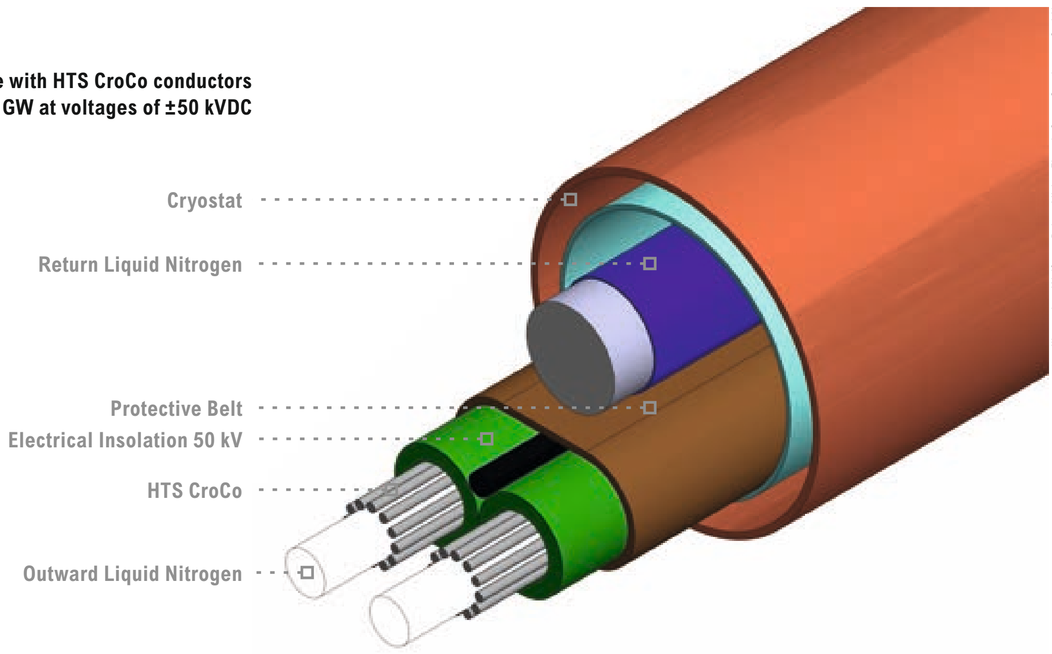


Illustration: Wolfgang Reiser, Vision Electric Super Conductors GmbH

An HTS CroCo is formed from numerous industrially manufactured HTS tapes

Vision Electric Super Conductors GmbH, Kaiserslautern, Germany

Superconductors can provide high magnetic fields for plasma confinement in an energy-efficient manner and are therefore indispensable for future fusion power plants. Until now, only the classic superconductors niobium-tin and niobium-titanium have been used for fusion coils. These have to be cooled to -269 degrees Celsius. Newer high-temperature superconductors offer a much wider range of applications in terms of temperature and magnetic field. The first generation of such high-temperature superconductors is currently being installed in the current leads of the international experimental reactor ITER, which is currently under construction.

At the Karlsruhe Institute of Technology, development continues: Based on a superior second generation, KIT has developed the HTS CrossConductor (HTS CrossConductor or „CroCo“ for short), building on its experience with superconductors in fusion. It enables simple and industry-compatible processing of HTS tapes provided by industry into high-current conductors in long lengths. In this process, numerous HTS tapes of two widths are joined together in a continuous process to form a cross-shaped cross-section. An HTS cross conductor made from three and two millimetre wide HTS tapes can be cooled at -196 degrees Celsius with liquid nitrogen, which is widely used in the industry; it carries a current of 1500 amperes for a diameter of four millimetres in self-field. If six- and four-millimetre-wide tapes are used, the current at a diameter of about eight millimetres is already more than 3000 amperes in self-field. Currently, it is being investigated whether the HTS-CroCo production method can be used for the „DEMO“ demonstration power plant following ITER.

The HTS-CroCo technology has been licensed to Vision Electric Super Conductors GmbH, Kaiserslautern (VESC). The company offers superconducting high-current transport systems, to transport direct current with high efficiency due to the lack of energy losses in superconductors. HTS-CroCo technology makes it easy to process HTS tapes in long lengths. This has already been demonstrated for HTS-CroCos of over 50 metres. In addition, the bundling of several HTS-CroCos can multiply the current carrying capacity. Such superconducting high-current cables can be used, for example, in electrolysis plants, where currents of 200,000 amperes and more are required. Another application is energy transport with high currents at low voltages over long distances. Since the HTS-CroCos require less space than conventional cables, this can be done in slim, underground routes. Vision Electric Super Conductors GmbH has presented an initial layout for such compact and efficient DC cables for grid expansion.

Photos: Walter Fietz, KIT

HTS CrossConductor with additional copper cladding

COATEC GmbH, Schlüchtern, Germany

Sustainable energy from nuclear fusion requires the heating of a hydrogen plasma to temperatures hotter than in the sun. Despite magnetic shielding, the steel of the fusion reactor's First Wall is exposed to extreme heat. Without protection, it would suffer softening and erosion by bombardment with particles from the plasma. Metallic tungsten is a suitable candidate for a protective layer because it has the highest melting temperature of all metals, is resistant to erosion and can quickly dissipate heat to the cooling circuit for energy extraction.

The technological challenge for COATEC GmbH is to create a tungsten layer adhering to the steel surface over a large area. If directly bonded to steel, the tungsten would detach during production or operation because of the strongly differing thermal expansion of the two materials. As a solution, a functionally graded adhesive layer was developed at KIT in collaboration with Forschungszentrum Jülich: Via several mixed steel-tungsten layers, the tungsten content is gradually increased until a pure tungsten top layer is applied. Such coatings survive fusion-relevant high heat flux loading scenarios without damage.

The coatings are produced at COATEC GmbH using vacuum or low-pressure plasma spraying. With this process, COATEC GmbH can produce all sub-layers in just one operation that is readily upscalable. This is necessary because of the large surface area of the first wall. With more than 1000 square metres of wall surface per reactor as well as additional replacement modules, the technological mastery here will open up a steady demand in the future.

Half a square metre by a quarter of a square metre: the project set a new size record for coated areas. The transfer of coatings from flat to curved First Wall surfaces is already being prepared and will be tested shortly.

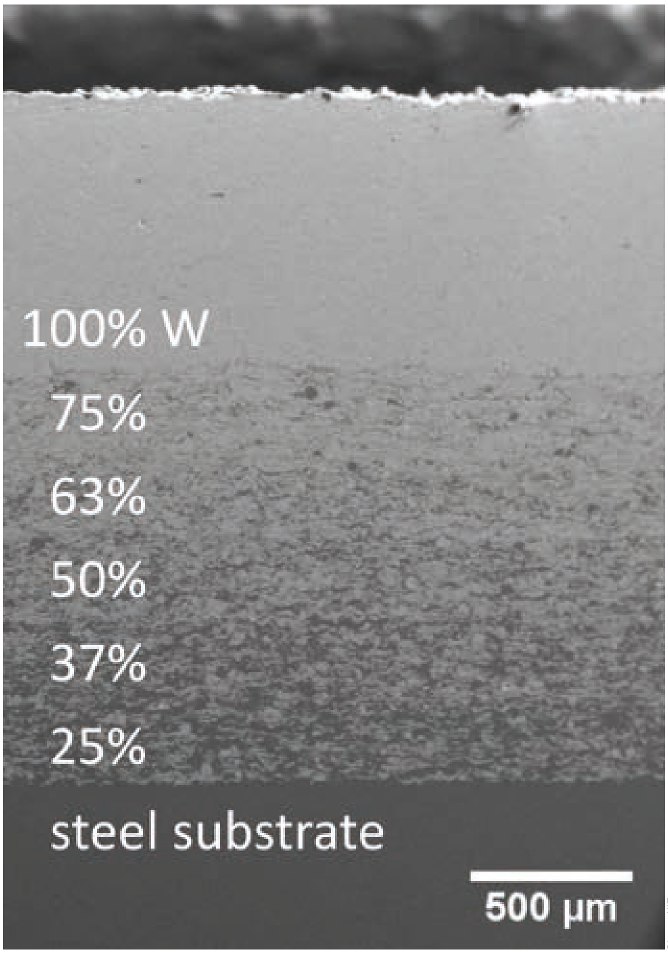


Photo: KIT

Structure of the protective layer

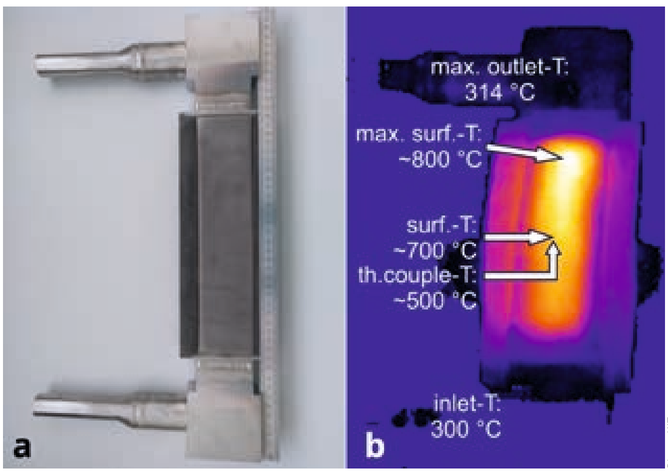


Photo: KIT

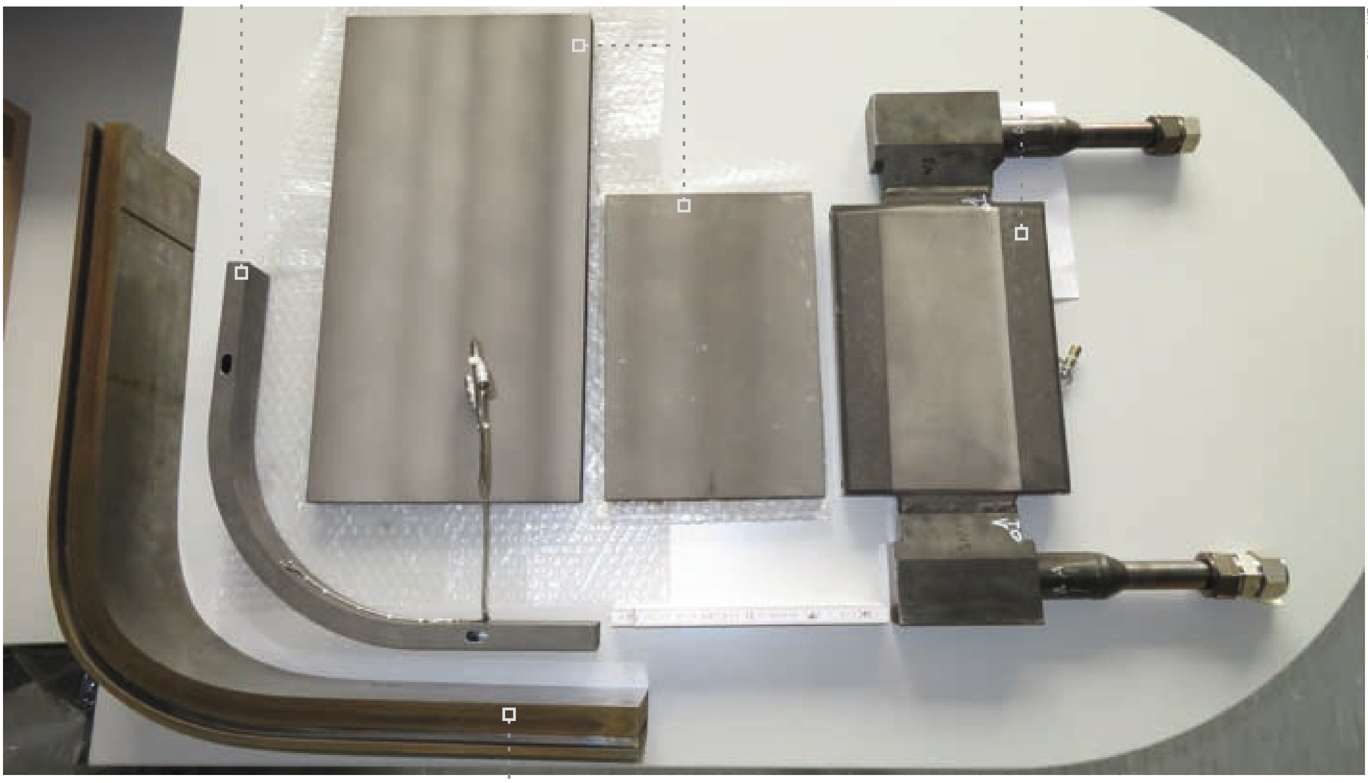
Left: Coated mock-up for high heat flux stress test.
Right: Surface temperature during stress test

Creating closed, adherent layers from tungsten is challenging. However, its high temperature resistance and simultaneous conductivity make it an interesting material for non-fusion applications as well.
By optimising its technology, COATEC GmbH is gaining valuable know-how for applications in other sectors, such as collectors in concentrated solar power plants or tungsten-copper components in high-voltage technology.

COATEC GmbH has been active on the market for high-quality coatings on gas turbine components for decades and works for all major original equipment manufacturers. The large vacuum coating systems built by COATEC have special features to make them particularly suitable for large components.
By operating two combined plasma spraying guns, COATEC GmbH achieves a uniform heat input into the components while maintaining maximum control over the component temperature during material application. In this way, COATEC produces protective coatings with optimum adhesion even on large surfaces and is ideally equipped for series production.

The coating of larger First-Wall elements with functionally graded layers on curved surfaces is strongly supported by the expertise in turbine blades. This implementation on the large First-Wall elements can be achieved by building large chambers for coating.

"Plasma Sprayed Plasma Protection" Functionally graded tungsten/steel coating for First Wall protection



Overview of current and future development steps of the tungsten protective layer.

It is designed to simulate the intense neutron radiation in future fusion power plants: IFMIF-DONES, the "DEMO-Oriented Neutron Source" of the International Fusion Materials Irradiation Facility, is a research facility being built in Granada, Spain. And the "Helium Loop Karlsruhe - Low Pressure" (HELOKA-LP) test plant, is an important component for the development of this facility.

With the help of IFMIF-DONES, new materials are to be irradiated and qualified for their use in near-plasma components of a first demonstration power plant. These materials must be resistant to high temperatures and high-energy neutron fluxes which are generated during the fusion process. In DONES, the fast neutrons that are typical for fusion are generated with the help of a particle accelerator. In particular, innovative types of steel are to be exposed to high neutron fluxes in optimised irradiation modules. Tests in the HELOKA-LP helium loop enable the development and optimisation of the irradiation modules.

Kraftanlagen Heidelberg, as general contractor, successfully mastered a number of challenges in the design, planning, construction and commissioning of HELOKA-LP:

▶ HELOKA-LP supplies the cooling gas flow through the irradiation module, with the flow reaching half the speed of sound. Either helium or compressed air can be supplied. Helium, as a monoatomic, light gas, requires the highest degree of leak tightness. Furthermore, the low absolute pressure level with simultaneous high pressure differences requires special management of the gas inventory. Therefore, the company developed an optimised start-up procedure.

▶ For the tests at the HELOKA LP facility, the neutron heating prevailing in IFMIF-DONES will be replaced by a completely new designed and constructed electric heating system.

▶ The plant is equipped with a helium supply system which includes a vacuum unit. It guarantees both the availability and the purity of the helium. This purity is important to avoid corrosion problems.

▶ Operating pressures, mass flow, and operating temperatures - it is possible to set a wide range of operating conditions at the inlet of the prototype irradiation module using a complex control system. This is necessary for the validation of the test module. A process control system (Siemens PCS7) controls and operates the system fully automatically.

Testing, testing, and testing! HELOKA-LP – Special materials require special test equipment

Kraftanlagen Heidelberg GmbH, Germany

The HELOKA-LP test facility at the Karlsruhe Institute of Technology

Photo: KIT

Helium plants with comparable parameters (mass flow up to 120 g/s helium, typical pressures 3 bar, drive power 350 kW) have not been built before. Thanks to the collaboration with the Karlsruhe Institute of Technology, Kraftanlagen Heidelberg, a member of the French Bouygues Construction SA, has been able to acquire new know-how in this field. The company is now ideally positioned to contribute to the future DONES cooling system and other subsystems, for example the remote handling facility of the plant. KIT has already successfully tested the first prototype of an irradiation module in the HELOKA LP plant.

Breuckmann GmbH & Co. KG, Heiligenhaus, Germany
Tokamak Energy Ltd., Oxford, Great Britain

Developing materials for future fusion power plants is the ultimate challenge for researchers and engineers. High-temperature and high-heat flux applications, such as those in fusion or, for example, with metal casting, require new approaches to traditional materials - such as the refractory metal tungsten. To overcome the intrinsic brittleness of tungsten, a fibre-reinforced tungsten composite is being developed. Adding high-strength and ductile tungsten fibres can reduce stress peaks. Brittle becomes tough: the material is now more resistant to crack growth and material failure. Two different manufacturing routes have been focused on: a powder metallurgy route with randomly oriented short fibres and production by chemical phase deposition on long fibres running in one direction.

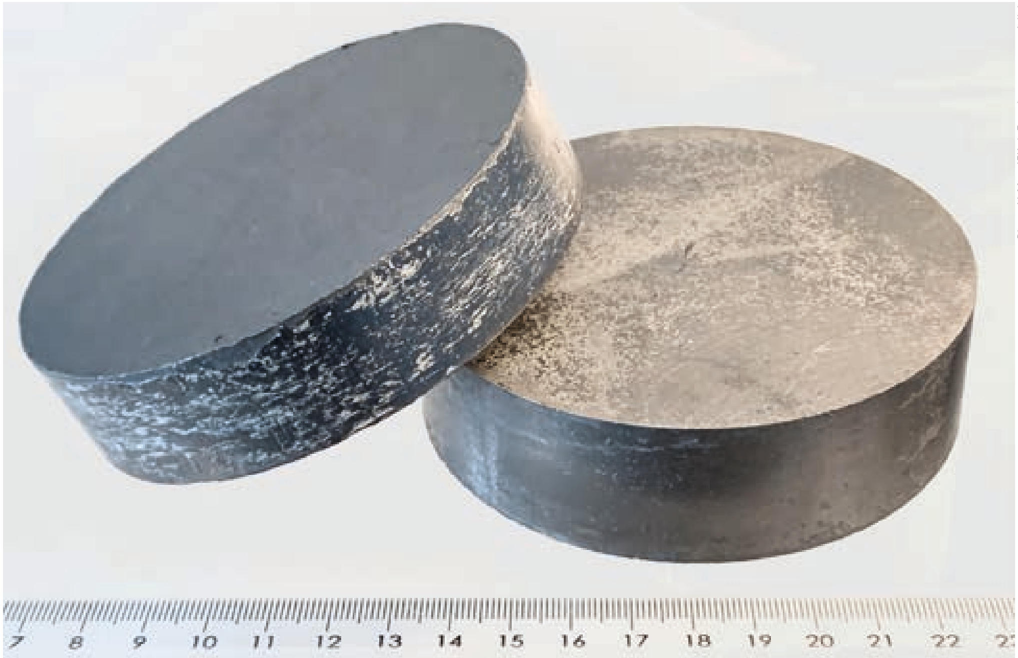


Photo: Y. Mao, IEK-4, Forschungszentrum Jülich

Material sample of tungsten fibre reinforced tungsten composite with dimensions of 105 mm x 30 mm.

As a result of comprehensive feasibility studies at Forschungszentrum Jülich GmbH and partner institutions the composites are now on their way to industrial application. In particular, the collaboration with partners from industry pushed it towards industrial production. Breuckmann GmbH & Co. KG and Tokamak Energy Ltd. both had their own requirements for the materials, e.g. high ductility and even higher thermal loads. This first production of samples of a size of up to 100 millimetres with a high material thickness was made possible by Breuckmann GmbH Co. KG within the European FUTTA* project and by Tokamak Energy Ltd.

The promising first results in terms of transferring the processes to an industrial scale and to alternative applications open the door for further development and application of tungsten fibre reinforced tungsten.

*FUTTA stands for Fusion Technology Transfer Activities. The consortium supports innovative projects in Europe by promoting fusion technologies and their application.

From brittle to tough
Tungsten fibre-reinforced tungsten composites for high-temperature applications

Hermle Maschinenbau GmbH, Ottobrunn, Germany

HIP supersonic production "Supersonic manufacturing" with cold gas spraying for DEMO First Walls

In fusion power plants such as DEMO, the first wall of the plasma vessel is one of the key components in terms of industrial production. The reason for this is not only its considerable height of ten meters, rather its complex 3D outer contour, which follows the plasma surface. On the surface of the first wall, a large part of the radiation energy from the fusion plasma is converted directly into heat. Cooling circuits transfer the heat to energy production systems. For this purpose, the thin first wall – the ratio of wall thickness to reactor size in DEMO is comparable to that of a chicken egg – must be completely equipped with close-meshed cooling channels. In addition, because of the gas cooling with helium, the inner surfaces of the cooling channels must be provided with a structure of topographic patterns in areas of local load peaks - in this way, the heat transfer from the structure to the fluid can be maximized.

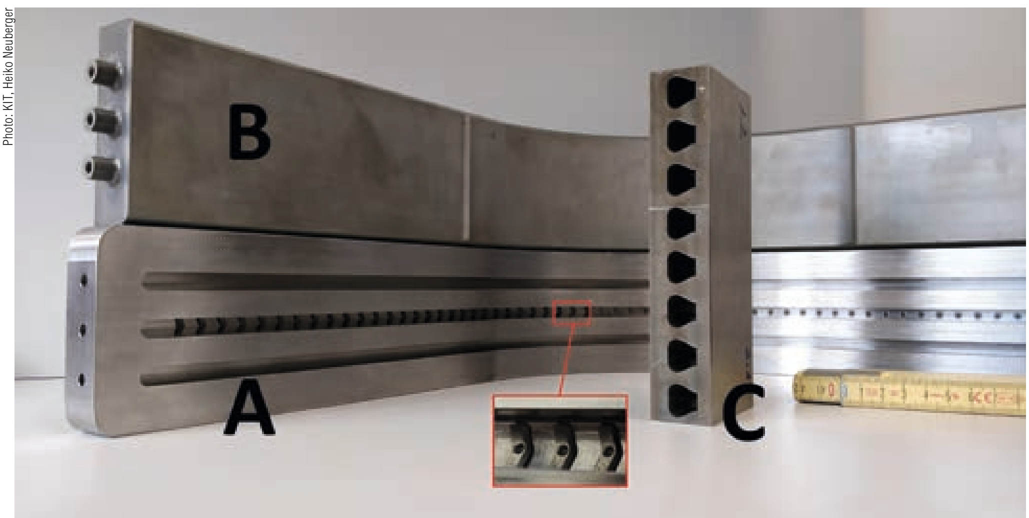
If all boundary conditions are to be fulfilled, conventional production methods offer hardly any possibilities for economic realization. Even additive manufacturing technology, used on its own, reaches its limits here. However, an innovative combination of Hermle's metal powder application (MPA) additive manufacturing technique, which utilizes a supersonic gas flow in a so-called cold gas spraying process, and the conventional joining process of hot isostatic pressing is very promising.

The semi-finished products used are preformed shells with surface-milled channels and internal structuring. They are prepared using conventional technology and then sealed by cold gas spraying using the patented MPA-process from Hermle Maschinenbau GmbH (HMG). This process makes it possible to join a later pressure-bearing structure by means of hot isostatic pressing, thus producing a thin-walled monolithic body with a minimum of welds.

The technical challenge facing HMG is to transfer the cold gas spraying process already established in mold making, including channel production, to a new process chain and new materials. The first demonstration parts confirm this: The manufacturing sequence works. Before it can be realized in full scale for nuclear fusion power reactors, the technology will be further developed and marketed step by step on a smaller scale towards DEMO. Areas of application here include the production of receivers for solar thermal power plants such as solar towers, and the production of seamless high-efficiency heat exchanger tubes. Europe is on the way to a CO_2-neutral energy supply – the new technology can already contribute to the transition!

> The contract enables HMG to expand its MPA technology not only in terms of its existing material portfolio, but also to take its first steps toward the energy supply market. "As an additive manufacturing service provider, we are always looking for new and challenging applications for our MPA technology. Creating free-form channels, processing challenging steels or manufacturing large components – in this order we can bring in and demonstrate all the strengths of our manufacturing process," HMG said. "In addition, the research project for nuclear fusion will also generate new knowledge regarding a material build-up on thin-walled semi-finished products, opening up further fields of application for our MPA technology."

Photo: KIT, Heiko Neuberger



A) Semi-finished product: preformed shell with surface-milled channels including internal structuring (so-called semi-detached ribs) in the center channel.
B) Component after sealing the channels with HMG's MPA process.
C) Section through a demonstration part

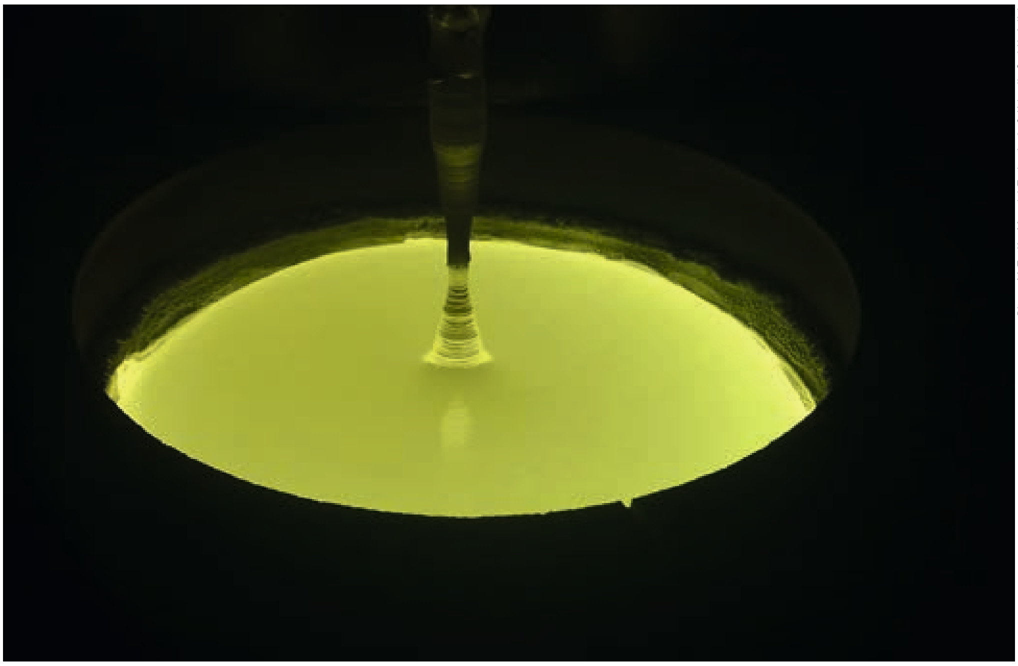
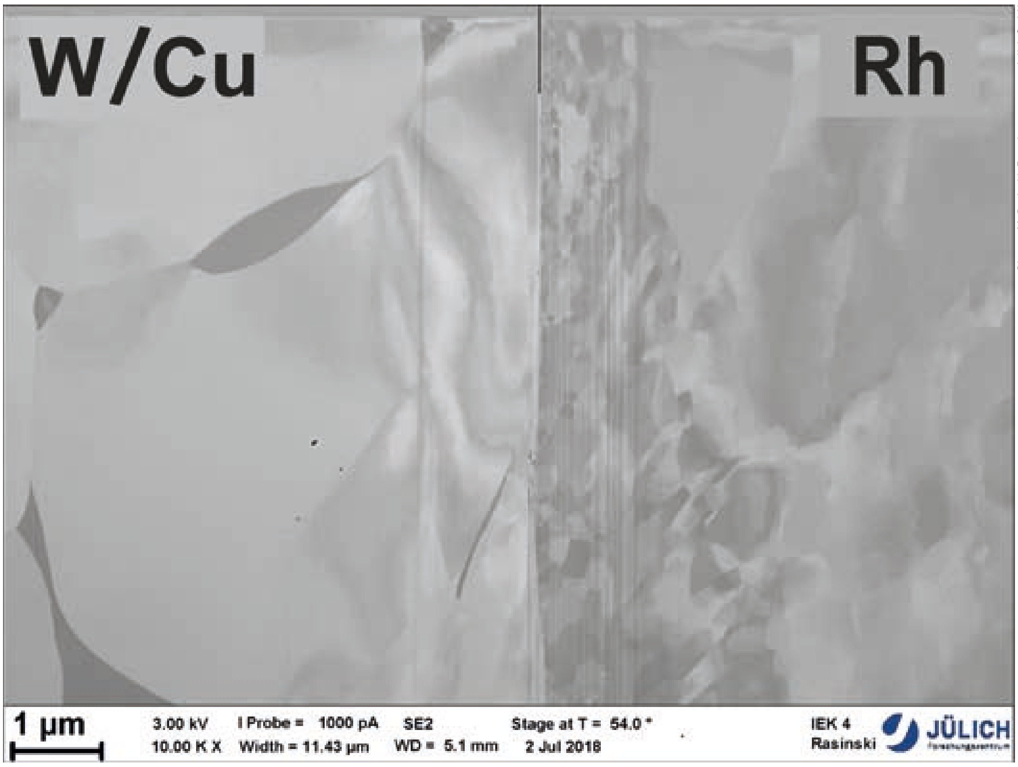


Photo: MaTecK – Material-Technologie & Kristalle GmbH, Jülich

A rhodium crystal is formed: crucible with the seed crystal immersed in the liquid rhodium

Crystal-substrate joint under the electron microscope



Photos: M. Rasinski, Forschungszentrum Jülich GmbH

MaTecK - Material-Technologie & Kristalle GmbH, supplier of innovative research materials, has specialized among other applications in growing metallic single crystals. Under the contract, the company expanded its capabilities to produce and polish large, high-quality single crystals. Thereby, it is now able to provide large customized rhodium crystals for various applications.

MaTecK –
Material-Technologie & Kristalle GmbH, Jülich, Germany

Numerous optical diagnostics in fusion facilities use complex mirror systems for measurements in the visible spectral range. The first mirrors of these systems face the hot plasma during the measurements. They have to withstand extreme conditions, for example bombardment with high-energy particles or very high heat fluxes. Provided that it is possible at all to clean the mirrors now and then, they must survive the long time between the rare cleaning phases without major damage. In addition, the mirrors should not oxidize even if some oxygen is present in the plasma chamber, be it due to contamination, during maintenance or in the unlikely occurrence of a water leak.

Rhodium is a very suitable mirror material, especially in monocrystalline and thus maximally homogeneous form. During exposure of a rhodium mirror to the plasma, the unavoidable material sputtering occurs more homogeneously than with other materials. Until now, however, monocrystals have only been available in small dimensions, in the size range of ten millimetres in diameter.

After many optimization steps, it was achieved: in cooperation with the technical experts of the Institute for Energy and Climate Research of the Forschungszentrum Jülich, Department of Plasma Physics, the company MaTecK succeeded in growing a large rhodium single crystal of a so far unattained size. They used an appropriately modified and upgraded crystal growing system for the melt at more than 2,000 degrees Celsius. From this crystal, a single crystal sample mirror was prepared with dimensions that are for the first time realistic and useful for the application, namely about 100 by 50 millimetres square and several millimetres thick. It is expected that scaling of the technology will make the production of even larger single-crystal mirrors possible. The single-crystal mirrors meet the high optical requirements: they are homogeneous in structure and their porosity is negligible. In addition, they have an excellent polishing quality: the roughness is less than one nanometre.

A mirror in a fusion device not only needs a well-reflecting surface, but also a robust mirror holder, which moreover requires water cooling. Using only rhodium for the entire mirror component would be expensive. Forschungszentrum Jülich identified a suitable substrate for a thin rhodium plate and successfully tested an adequate technique for joining the two layers. With the single crystal rhodium, fusion research now has a new material option that can be used in the diagnostic mirror systems of the experimental reactor ITER in southern France.

Monocrystalline rhodium mirror

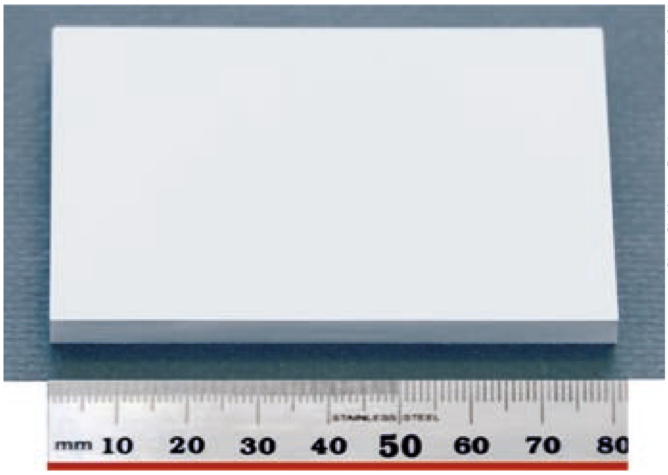


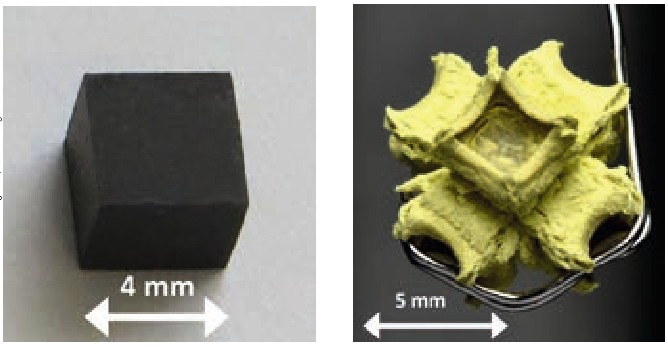
Photo: Ph. Mertens, Forschungszentrum Jülich GmbH

Mirror, mirror on the wall
Highly resistant mirrors for optical diagnostics in fusion facilities

Photo: Zoz GmbH; Wenden

The successful step from laboratory scale to the production of larger quantities of "smart alloys" is crucial for the possible use of such concepts in future fusion reactors. For Zoz GmbH, this represents a technological gain that significantly improves its market potential in fusion technology, especially in the development of plasma-facing materials and components. Already the first tests at Zoz GmbH to produce a smart powder, supported by EUROfusion, were successful. This paves the way for further industrial application.

Photos: T. Wegener, Forschungszentrum Jülich GmbH



The smart alloys (left) have at least ten thousand times the oxidation resistance of pure tungsten (right). The picture shows results of a 10-hour oxidation at 1000 degrees Celsius in an atmosphere with 20 percent oxygen.

Developing a future demonstration power plant (DEMO) raises unique challenges for scientists and engineers. These include replacement of established materials with new material concepts for many components so that these can withstand the extreme conditions – for example, the high particle and heat fluxes. Tungsten is expected to be used for the walls of the plasma vessel in future fusion power plants because of its favourable properties. However, it has the disadvantage that it oxidizes in the event of an air ingress, where the oxides then could potentially contaminate the environment. So-called "smart alloys" can significantly reduce oxidation. Lighter metals such as chromium are added to the heavy metal tungsten to achieve this, giving the alloy different properties: During normal plasma operation, these lighter components of the alloy are the ones that are sputtered first, so that the remaining surface of the affected

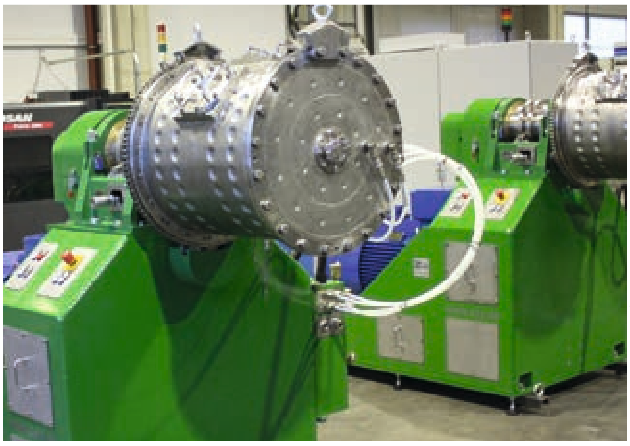


Photo: Deutsche Bundesstiftung Umwelt

Production hall (left) and simoloyer© industrial facilities at Zoz GmbH (small picture)

Smart alloys Innovative manufacturing routes for new materials

Zoz Group, Wenden, Germany

component is almost pure tungsten, with the corresponding robust properties of this material. However, when an ingress of air occurs, the hot tungsten oxidizes at the surface. The light elements that remain re-accumulate there and slow down further oxidation of the component. These smart alloys thus show a high oxidation resistance compared to pure tungsten.

The DEMO fusion power plant requires an estimated 60 tons of the unique oxidation- and plasma-resistant alloy. Following extensive basic research and feasibility studies, the Smart technology must now be brought from laboratory scale to production. Here, innovative approaches are also being pursued. So-called mechanical alloying is an important development step in Smart technology: The alloying elements tungsten and chromium are pressed together so strongly through mechanical friction that an alloy is produced at room temperature simply by mechanical interaction. This is where the unique expertise of Zoz GmbH, an industrial partner of the EUROfusion consortium, comes into play. The company‘s alloying technology already enables both the production of several hundred kilograms of the alloyed material and a continuous alloying process.

NTG Neue Technologien GmbH & Co. KG, Gelnhausen, Germany

Cooling dress for hot days
Heat exchangers for Wendelstein 7-X pipes


Photos: NTG Neue Technologien GmbH & Co. KG

Water-cooled port liners

Wendelstein 7-X is progressing towards completion. All elements that come into thermal contact with the plasma will be actively cooled with water in the future. This also includes the ports, which connect the plasma vessel with the outer vessel and serve to observe and supply the plasma. To prevent the ports from inadmissible heating due to thermal radiation from the plasma, and with them the cryogenic chamber, they must be protected with water-cooled liners. These 86 „port liners" are developed and manufactured by NTG Neue Technologien GmbH & Co. KG.

The technical challenge faced by the mechanical engineering company was the combination of high power input, tight tolerances and the use in ultra-high vacuum. The cooling system is designed for a power input of 50 to 100 kW/m^2 and functions as a heat exchanger: cold water flows in four millimeter-thin tubes, which in turn are located in eight millimeter-thick tubes. The return flow then takes place in the space between the two pipes. This design allows manufacture of differently shaped port liners – round, rectangular or oval – that fit precisely into the narrow installation spaces of 15 to 20 millimeters.

"The order has allowed us to expand our vertical range of manufacturing capabilities," says NTG Neue Technologien GmbH & Co. KG. More than 10,000 four- and eight-millimeter tubes were cut to length for each of the port liners and their ends prepared for welding. The company set up a lathe workstation and operated it partly in three shifts. To weld the end caps to the eight-millimeter pipes, it purchased an orbital welder and trained its employees accordingly. The ring manifolds, which distributes the water to the individual pipes, and other components of the port liner are machined from sheet metal. For this purpose, NTG purchased a waterjet cutting machine and integrated it into the manufacturing process. The company installed various measuring devices for the extensive testing of the port liners, e.g. to detect leaks at 160 degrees Celsius and 25 bar in the port liner. NTG: "We also benefit from these enhancements for other orders. We now have the opportunity to use the developed technology elsewhere."

From the eye of a needle to the eye of a needle Special tools for the assembly of Wendelstein 7-X ports

Fantini Sud SpA, Anagni, Italy

More than 250 steel tubes, so-called ports, connect the plasma vessel to the outside world, passing through the ultra-cold area of the coils. Some of them accommodate diagnostics and antennas for plasma heating while others are used to provide connections to the vacuum pumps and to supply and monitor components in the plasma vessel. The ports are between 1.4 and 2.5 meters long, have diameters of 0.1 to 1 meter and weigh between 100 and 1,000 kilograms. Fantini Sud developed, qualified, and supplied three ramps for the port assembly. They enabled the ports to be aligned and installed with six degrees of freedom and an accuracy of up to 1.5 millimeters.

The job was a challenge for Fantini Sud: The ports had to be aligned and inserted with high precision; at the same time, large loads had to be controlled. The threading process through each of the two eyes of a needle, one opening in the outer vessel and the corresponding one in the plasma vessel, required repeatability and extreme controllability. A flexible configuration of the ramps and interchangeability of the attachment interfaces for the different port shapes – round, oval or rectangular – were also required.

About two thirds of the ports are used for diagnostics. One of these is a laser diagnostic, which – by scattering light at the free electrons – allows the measurement of the temperature and density of the plasma without contact (Thomson scattering). This special diagnostic system is installed on a walkable support structure, which must be mechanically decoupled from the plasma and the outer vessels. This allows the required millimeter-precise alignment of the optics and laser mirrors to be unaffected while the system is in operation. The support structure is connected to a tower-like steel structure inside the experiment, which accommodates numerous cable and pipe routes. Fantini Sud designed, manufactured, tested and assembled both stainless steel support structures, thus significantly expanding its expertise. At that time, it was one of the first Italian companies to be qualified and certified according to European standards to carry out steel and aluminum support structures and the related welding processes.

The advancement in design and manufacturing technologies required for this order and the high quality assurance requirements led to a significant upskilling of the company, forming a valuable pool of experience and providing Fantini Sud with appropriate credentials. The improvement in the field of welding and the increase in the overall level of quality and in all manufacturing aspects were strategically significant for the company's rating. They paved the way to acquire the necessary qualification and, consequently, orders from other international customers such as the European nuclear research center CERN, the European laser research project ELI, and the French company CNIM.

Port assembly

Photos: IPP, Beate Kemnitz

Photo: IPP, Beate Kemnitz

Switching stage racks for the high-voltage DC power system

Ampegon Power Electronics AG, Baden, Switzerland

High tension and durability
Development of a high voltage DC power system

With the development described here on the right, the high-voltage power systems of Ampegon Power Electronics AG are now in a better position on the world market.

A 130 kilovolt high-voltage DC power supply with a peak performance of 39 megawatts in continuous operation has been developed for the various heating systems of Wendelstein 7-X. Above all, this power system, which has been recently expanded to ten modules, must fulfil the high demands of the microwave tubes. The normal systems available from Ampegon, formerly Thomson Broadcast, had to be improved in order to reach the necessary specifications. Most importantly, the control precision has been improved, while increasing the voltage range and optimising the quality of the direct current, in particular the residual ripple.

Dockweiler AG, Neustadt-Glewe, Germany

A total of four thousand five hundred meters of pipes for cooling water are installed in the plasma vessel of Wendelstein 7-X, in order to cool the wall elements exposed to very high heat fluxes. The complex shape of the plasma vessel determines the shape of the coolant pipe system, which could only be manufactured with great difficulty using conventional procedures. Above all, welding all the precisely aligned branching connectors would cost a great deal of time. Dockweiler AG found a solution: the company is capable of installing the extrusions or so-called “necks” at an angle of up to 60 degrees on the pipes. Thus, the connecting pipe can be connected to the finished neck by means of well-defined and highly precise orbital welding techniques.

Dockweiler first began manufacturing three-dimensional pipe systems with the contract for Wendelstein 7-X. The company created their own new measurement and bending techniques from scratch and acquired the corresponding machines. As an additional requirement, Dockweiler had to first master the special quality requirements of ultra-high vacuum technology. The knowledge acquired during this process has provided Dockweiler access to new fields of business: “We are now also active for ITER. Furthermore, we also receive enquiries for smaller but special components in similar fields.”

Steel pipe spaghetti
Cooling tubes for the components in the plasma vessel

Photo: IPP, Anja Richter Ullmann

Coolant pipe system for the cryostat and the plasma vessel of Wendelstein 7-X

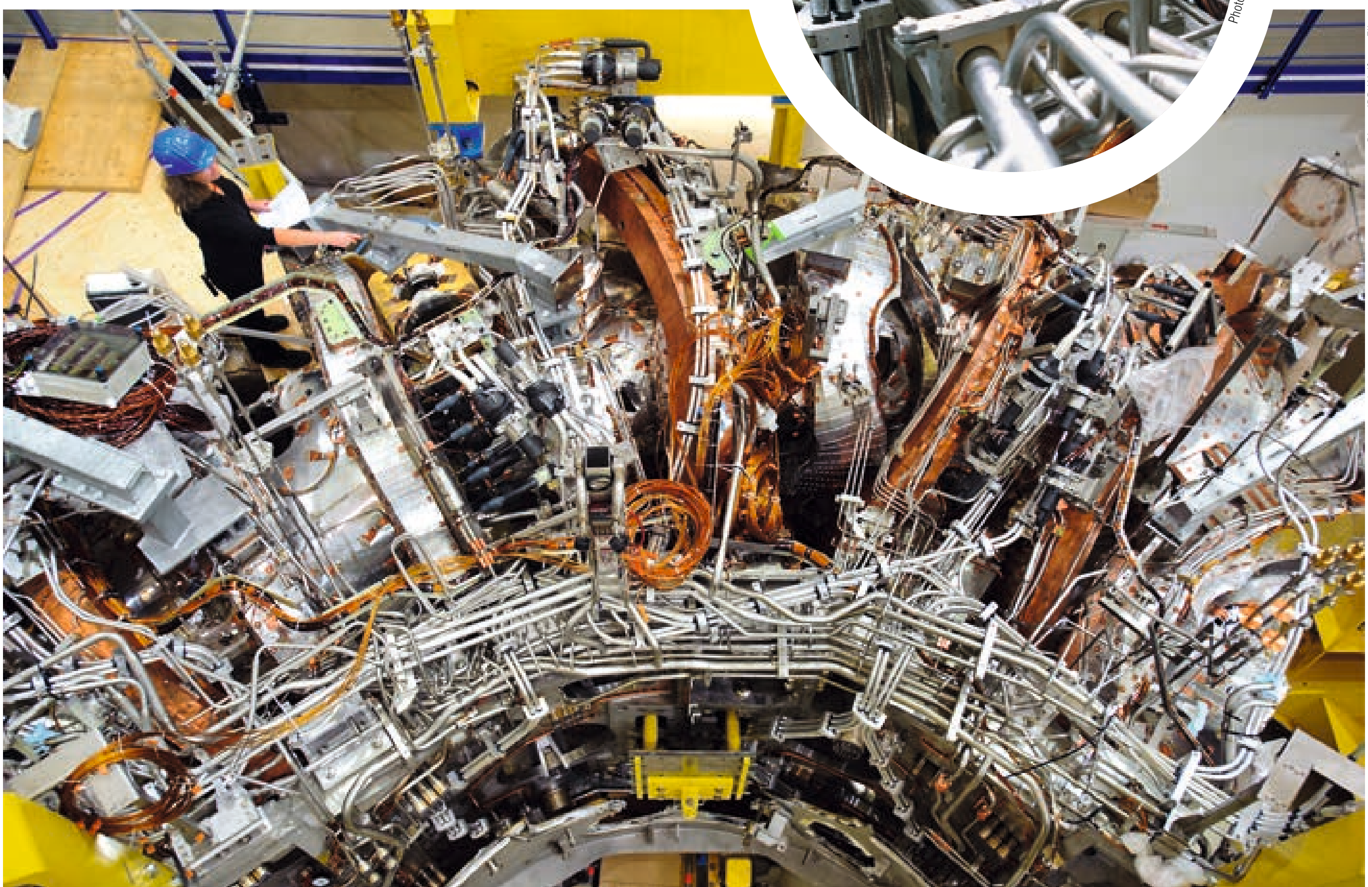


Photo: IPP, Wolfgang Filser

Micrometer precision work Mechanical machining of the central ring

CLP Srl, Borgo San Dalmazzo, Italy

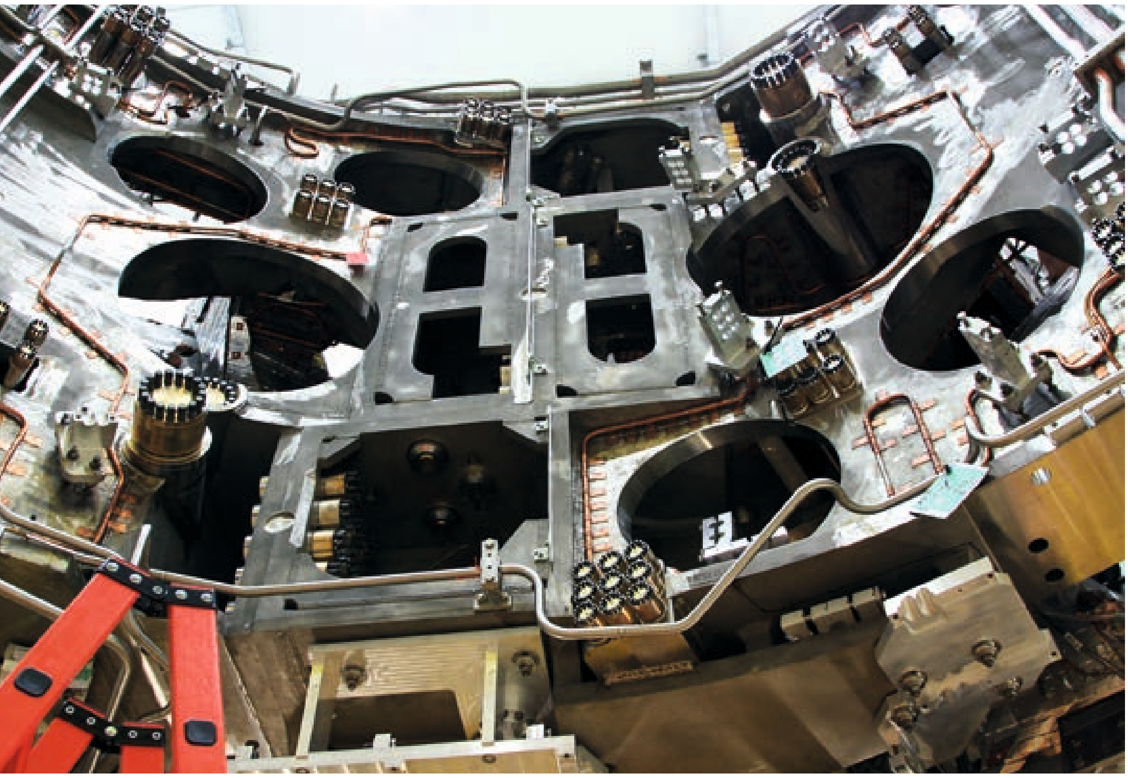


Photo: IPP, Beate Kemnitz

Wendelstein 7-X central ring

Working on the Wendelstein 7-X central ring has opened completely new areas of work for the company, as well as additional fields for contracts. The pre-machining of coil components for the international experimental reactor ITER and the final machining of coils for the Japanese-European fusion device JT-60SA, for which CLP also designed and manufactured the coil transport kits – these are all activities that have resulted from the cooperation with IPP.

The superconducting magnetic coils for Wendelstein 7-X are bolted to a massive central ring. This steel ring is subject to forces of roughly 100 tons. For that reason, the ten individual ring segments had to be positioned with high precision. The steel segments weighing several tons and standing several meters high were transported to CLP in northern Italy for the mechanical finishing of the metal surfaces with a precision of roughly 100 micrometers (100 millionths of a meter) using a milling machine. During the process, they each had to be re-chucked several times. Special techniques had to be developed, which could guarantee precise, reproducible positioning despite the size and weight. Additionally, the workshops had to be equipped with thermostats to achieve the required operational precision. IPP and CLP designed and successfully implemented computer-controlled measurement procedures to check the precision. Special deep drilling techniques were developed for connecting the segments to each other using long screws made of special steel.

Nord-Lock AG, St. Gallenkappel, Switzerland
Tempelmann Feinwerktechnik GmbH, Pinneberg, Germany

Photo: IPP, Jörg Riemann

Photo: IPP, Jörg Riemann

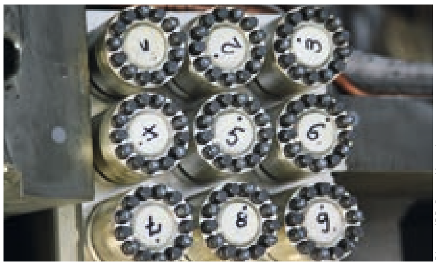


Photo: IPP, Beate Kemnitz

Wendelstein 7-X: Bolt connections on the central ring

Not even the bolts of Wendelstein 7-X are purchased off the rack. High-tech products were used to bolt the individual segments of the central ring of Wendelstein 7-X to each other. The 70 superconducting coils are fastened to the ring using bolt connections. These guarantee a certain degree of flexibility in comparison with welding. During operation of Wendelstein 7-X, these bolt connections bear heavy loads created by the combination of magnetic forces and extremely low temperatures (-270 degrees Celsius). Nord-Lock AG, the inventor of the Superbolt system, provided bolts for Wendelstein 7-X, which are made of high-strength Inconel 718 with threads between M20 to M90 and lengths between 100 and 1350 millimeters. The Inconel 718 material used for the bolts has a significantly higher strength than is usual in the trade and was supplied by Tempelmann Feinwerktechnik and BGH Edelstahlwerke Freital. Tempelmann has been able to produce the material with a high degree of process reliability after a series of various tests, including tests at low temperatures.

Photos: Tempelmann Feinwerktechnik GmbH

View into the lathe: Inconel 718 is dry machined with ceramic plates. The red-hot chips are removed – the bolts emerge.

Inconel 718 bolts for IPP – high-tensile and corrosion-resistant

Bolted, not welded
Ongoing development of bolt connections

Machining the Inconel 718, which is particularly difficult to process, was a challenge for man and machine.

However, the coefficient of friction of the bolts did not yet meet the requirements for Wendelstein 7-X: the lower the coefficient of friction, the less force is required to tighten the bolts. For that reason, Nord-Lock developed a dual phase solid coating for the bolts. This special development for Wendelstein 7-X and the simultaneous usage of silver-coated nuts and thrust washers reduced the coefficient of friction to 0.06. Previously, this coefficient was in the range of 0.12 to 0.14 while using special lubricants. Moreover, there is no need to re-lubricate hundreds of bolts during re-assembly, as the exceptionally low value remains constant over multiple clamping procedures. The low coefficient of friction also allows the use of smaller torque wrenches, which simplified assembly in the very restricted construction space at the fusion research facility.

High levels of tension can be achieved quickly thanks to ongoing development of the Superbolt system and a new procedure for tightening the nuts. This is now standard procedure at Nord-Lock AG. Tempelmann Feinwerktechnik GmbH states: “This basic research has also qualified us for other projects. We can therefore confidently claim to be a specialist for machining Inconel in age-hardened states. The cooperation with the international team of researchers has enriched us in dealing with problems, reduced our fear of contact and influenced us positively.”

RASI Maschinenbau GmbH, Illingen, Germany

A colossal cable harness
The superconducting bus system for Wendelstein 7-X

The 70 superconducting coils of Wendelstein 7-X must be electrically and hydraulically connected to each other as well as to the current leads. This is done by 124 three-dimensionally pre-formed superconductors. Thin filaments of the niobium-titanium superconductor are embedded in copper wires that are twisted into a cable. Liquid helium for cooling at the required temperature of -270 degrees Celsius flows between the individual wires. The cable itself is enclosed in a helium-tight aluminum case. Unlike the wire harness in a road vehicle, for example, the shape of the connecting lines cannot be adjusted on site because the superconductor cable is not flexible. The cables thus have to be prefabricated with a high accuracy of just a few millimeters. This made it necessary to build and qualify a computer-controlled bending machine.

The company RASI and the Forschungszentrum Jülich have jointly developed an instrument that allows bends to be realized in two directions. Normally, a variable bending direction is made possible by rotating the piece about its axis. Here, however, we were dealing with pre-formed parts of several meters in length, which, during rotation would have swung freely in space, even below floor level. The novel two-directional bending machine allows the piece always to be turned upwards, and hence makes the whole manufacturing process possible at all.

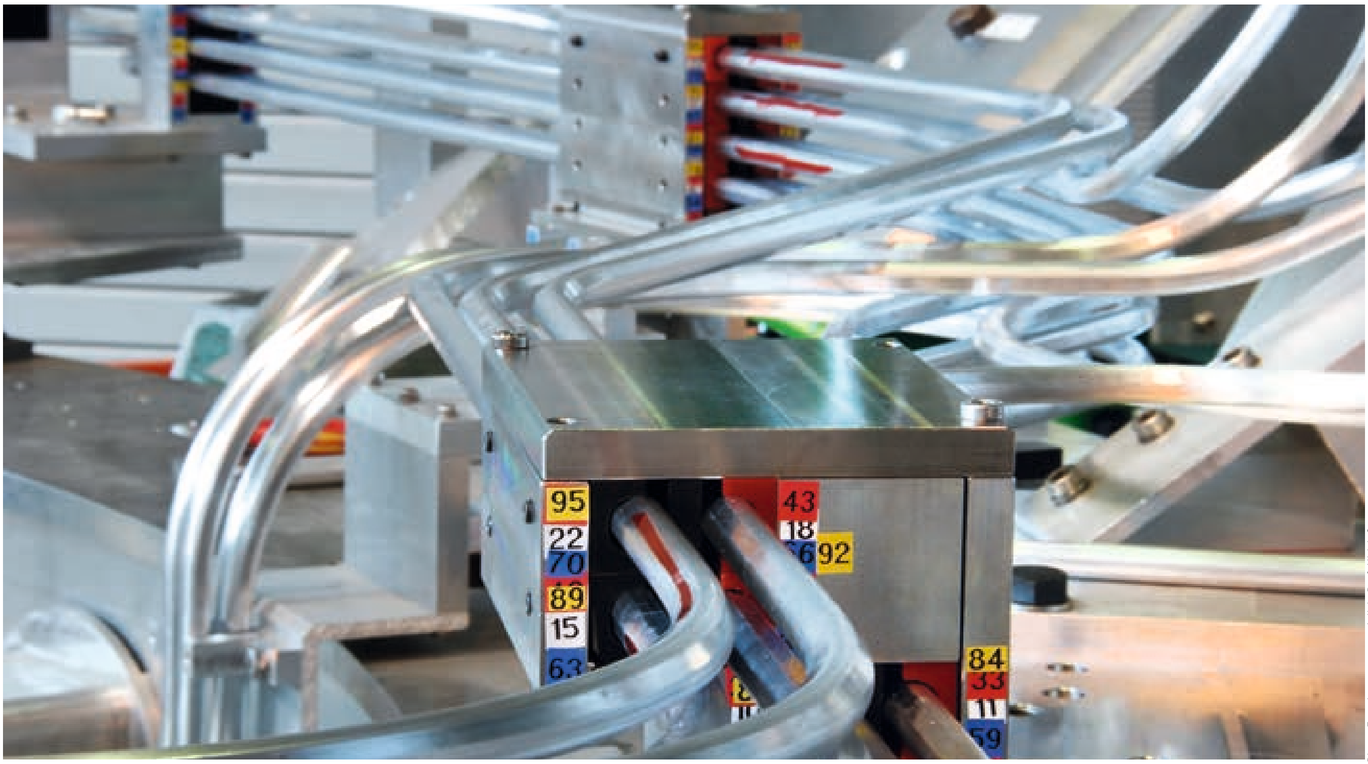
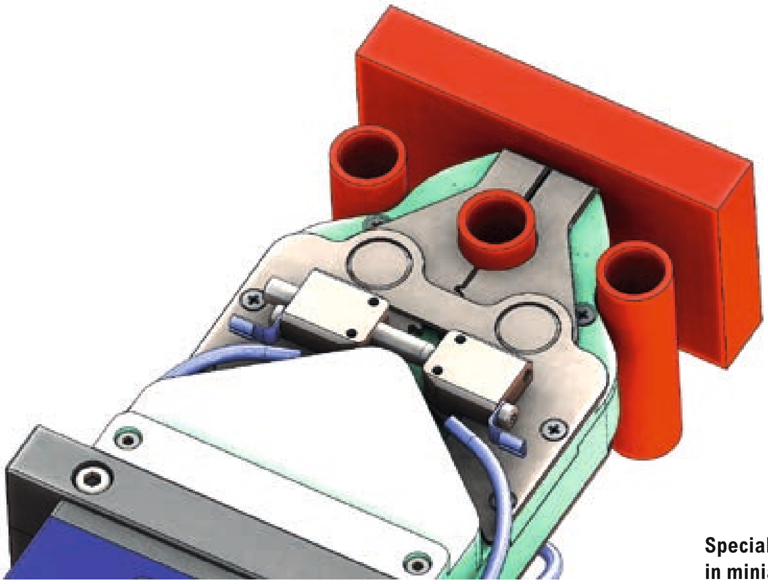


Photo: Forschungszentrum Jülich, Prof. Ulrich Samm

Geometric check of shaped superconductors

The experience gained in developing this new machine is valuable for future customer-specific developments by the manufacturer. The new and more flexible bending machine has found customers in engine, turbine, and shipbuilding. It entered series production.



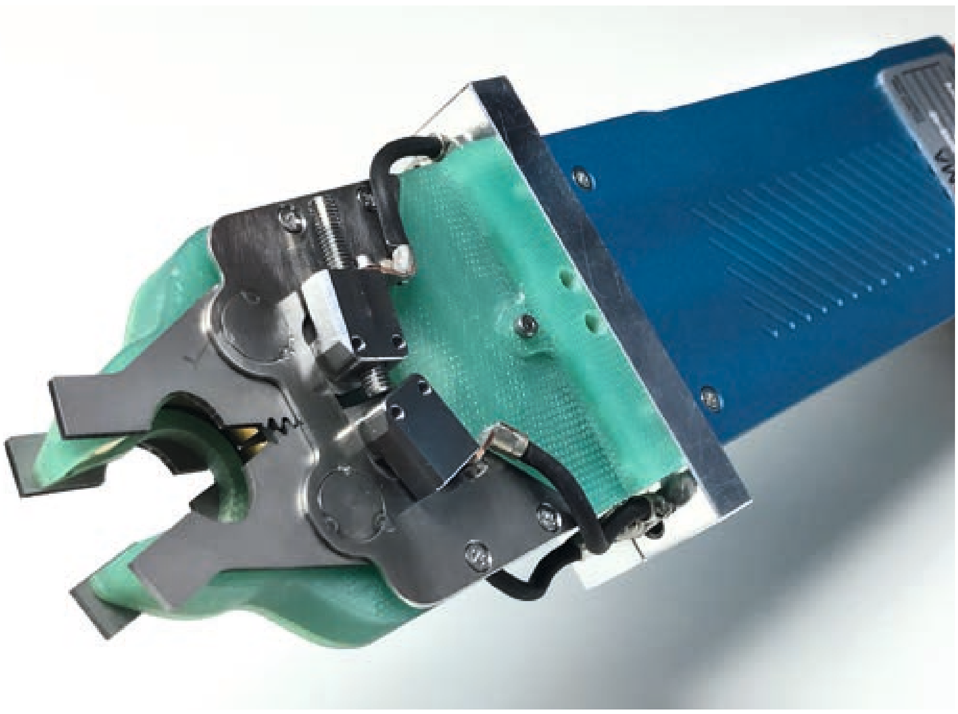
Special welding head in miniature format

Encoma GmbH, Eigeltingen, Germany

Small but mighty
Orbital welding head for confined spaces

High-precision orbital welds of the cooling water pipes near the wall of the Wendelstein 7-X fusion device have been performed under extremely tight space conditions in the plasma vessel. In 2019, the special machine builder Encoma developed a mini orbital welding head for this purpose with a particularly thin rotor and a clamping system that can be opened to the side with a space-saving compact design. This new design allows the welding of large pipe diameters – with respect to the size of the welding head – while at the same time it minimizes the radial and axial space required around the weld seams.

IPP funded the development of this technology, which is now ready for application here and elsewhere. It has already been used for welds on divertor piping systems of the ITER project and will soon be used at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt. According to the company, a very similar design of this concept is now also being used successfully for complex piping on ultra-pure gas supplies for production plants in the semiconductor industry.



Bye-bye, space problem! Cable bending for ASDEX Upgrade

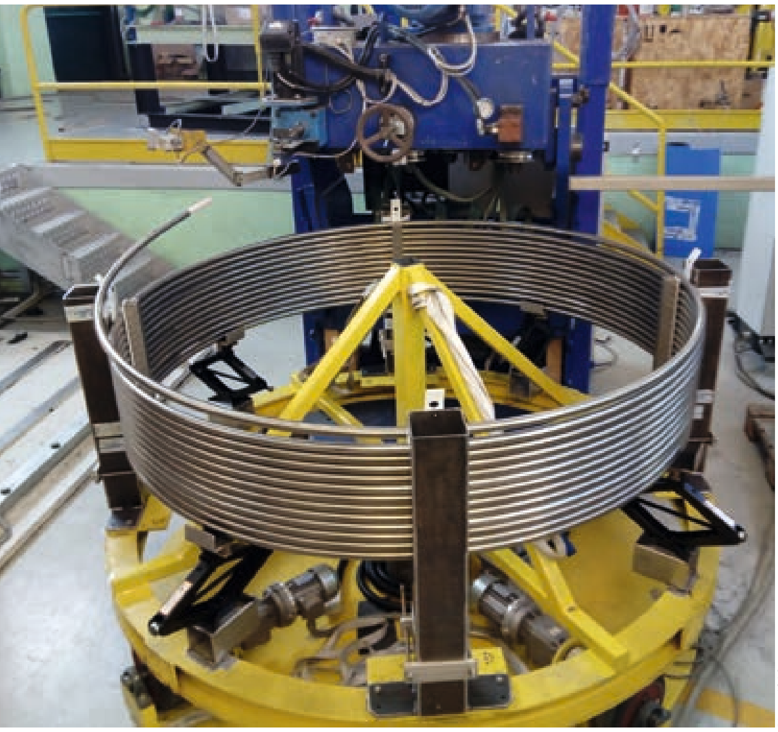


Photo: ICAS

Production of the TIC conductor

ICAS Consortium, Frascati, Italy SeaAlp Engineering Consortium, Genua, Italy

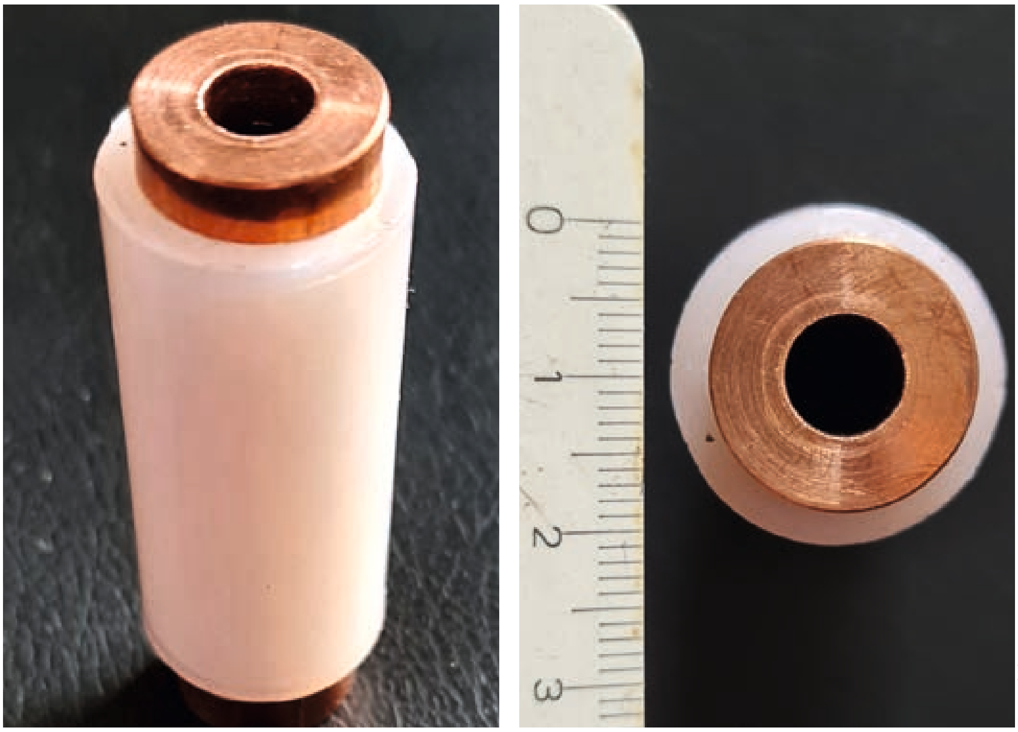
ASDEX Upgrade at the Max Planck Institute for Plasma Physics in Garching is the largest national tokamak fusion device in Europe. To control the interaction between the hot fusion plasma and the surrounding walls, ASDEX Upgrade is equipped with a particular component, a "divertor". It generates a special magnetic field, that directs the plasma edge towards robust, water-cooled target plates mounted on the vacuum vessel wall.

Investigating "alternative" configurations for the divertor is the next major step in the ASDEX Upgrade research programme. The aim is to spread the magnetic field lines in the divertor area by distributing the energy flow along the field lines so that it covers a larger area of the target plates, thus reducing the local heat load.

In 2016, the project to develop and install the new divertor was launched. It will complement the "classic" divertor at the bottom of the vacuum vessel and will be located at the top of the vessel. The required magnetic field will be generated by two coils to be installed inside the vacuum vessel. The product of coil current and number of turns will be up to 52 kiloamperes-turns. Moreover, voltages of up to one kilovolt per turn could be induced in the coils during operation under certain circumstances, which is why the coil conductor has to meet special requirements. To avoid arcing between adjacent turns, the copper conductor is placed in a protective tube made of stainless steel. This protective tube acts both as an electrical shield and as a vacuum barrier. A 2.5-millimetre-thick Tefzel or Teflon coating (Tefzel-Insulated Conductor, TIC for short) provides the insulation between the water-cooled copper conductors.

With a diameter of 26 millimetres, the stiffness of the conductor is impressive – similar to that of a typical stainless steel handrail. Due to the limited access, it is not possible to bring a complete coil into the vacuum vessel. Therefore, the coil must be bent inside the vacuum vessel. Hence, two tasks need to be solved. The first one is to produce a special conductor adapted to the requirements of ASDEX Upgrade and the second is to develop procedures for bending the coil inside the vacuum vessel and design the required tools.

Both tasks are being worked on in cooperation with external companies. The TIC conductor was manufactured in cooperation with the ICAS consortium based in Frascati/ Italy. ICAS has experience in the production of water-cooled



Photos: ICAS

Tefzel-coated copper – the conductor without the sheath

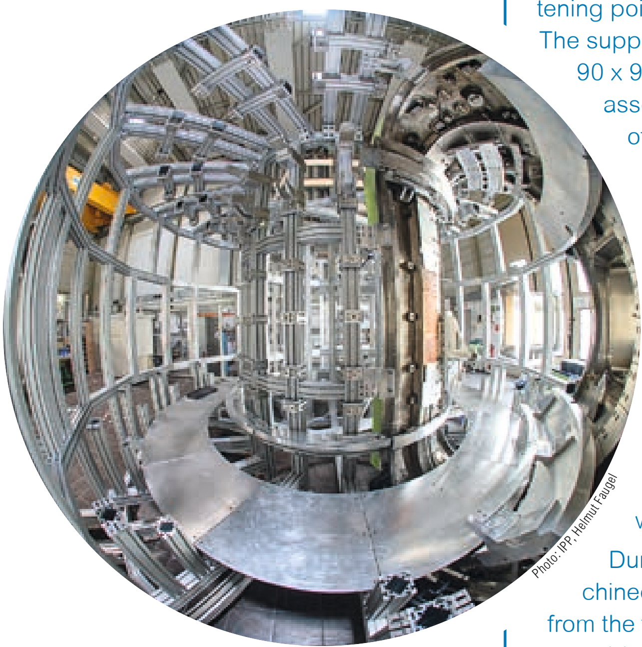
conductors with stainless-steel sheaths electrically insulated with ceramics (magnesium oxide), as required for the international experimental reactor ITER. However, the TIC conductor for ASDEX Upgrade has new requirements. Tefzel is to be used as the insulation material instead of ceramics because it is easier to handle than the hygroscopic magnesium oxide. The conductor qualified and produced for ASDEX Upgrade can also be used without problems for other fusion facilities of comparable size, i.e. with similar coil current.

The SeaAlp consortium, based in Genoa/Italy, has the expertise in bending conductors for coil manufacturing. However, the experience gained with fusion devices such as ITER and Japan's JT-60SA had to be adapted to the specific task at ASDEX Upgrade – bending a coil inside a vacuum vessel under limited space conditions. While the larger coils at ITER or JT-60SA are bent during the assembly of the fusion devices, at ASDEX Upgrade the coils are bent for the first time directly inside the vacuum vessel. A similar procedure is planned later for coil assembly in the vacuum vessel of ITER.

"The work carried out for ASDEX Upgrade has allowed us to develop a specific expertise for in-vessel coil winding, with particular attention to optimizing the geometry and dimensions of the winding equipment. We are confident that this knowledge will generate new business opportunities with other experiments in the field of fusion energy" says the SeaAlp consortium. For the ICAS consortium, the collaboration with IPP also proved fruitful. Optimization of the processes needed for the Teflon-based high-temperature copper insulation to avoid impurities and achieve the required tolerances, or handling the insulated copper conductor during the steel sheathing process have been developed. The requirements set by the project challenged the joint team in both the development and production phases. "The newly acquired expertise is currently being applied in the production of the mineral-insulated conductors with stainless steel sheath for the ITER in-vessel coils system" says ICAS.

Bauer Profiltechnik GmbH, Neckarwestheim, Germany

Promotional dummy
Profile-frame polygon for trial assemblies – a second ASDEX Upgrade



The assembly test stand

Bauer Profiltechnik, a specialist in tailor-made work stations, has developed an innovative, 3.5-meter-high and 4.5-meter-wide frame that accommodates the fastening points – and on this, the two-ton components. The support system is a 16-cornered polygon. From 90 x 90 millimeter thick profile struts, the designers assembled 8 x 32 connections at an exact angle of 11.25 degrees each. Thereby, IPP required a deviation tolerance of less than one millimeter. “The result is a small masterpiece even for us,” Uwe Wehle, Managing Director of Bauer Profiltechnik, sums up the high-publicity showcase project. “Thanks to the modular and strut-like construction method in which we designed and manufactured the frame, the mock-up is also designed to be highly flexible in terms of adaptation, adjustment or extension without the need for special tools and combined with enormous time savings.”

During the entire process, the material was machined at a temperature of 20 degrees Centigrade from the first to the last work step. “In this way, we were able to achieve a tolerance accuracy of 0.5 millimeters and to align the frame in Garching with an accuracy of up to two millimeters,” the company says on its website. “With the polygon we realized for IPP, we have created a project that illustrates the wide-ranging design options and possible applications of profile frame solutions. Such tailor-made solutions can be applied to almost any work and activity field in any industry and optimize the processes there.”

CAD image: Bauer Profiltechnik GmbH

A scale model

A second ASDEX Upgrade, but without vacuum vessel and coils: a test stand is used to practice the assembly of the new divertor, which is to be installed in ASDEX Upgrade as from 2022. Experience with earlier reconstructions of the fusion research facility has already confirmed that the testing of installation sequences and the trial assembly of components significantly facilitates and accelerates the time needed for the subsequent assembly at ASDEX Upgrade. The ninth octant – the prototype for the eight sections or "octants" that make up the steel plasma vessel of ASDEX Upgrade – has so far been used for these trial assemblies. Under a contract from IPP, Bauer Profiltechnik GmbH has now supplemented the ninth octant with the seven missing octants to form a ring vessel or "torus".

The seven new octants shape the torus using aluminum profiles. These struts must correctly reproduce all the fastening points to be used in ASDEX Upgrade. Keeping these points in the correct positon is important to ensure that the pre-assembled components will later fit onto the fastening points in ASDEX Upgrade. The plasma vessel of ASDEX Upgrade was measured for this purpose using a tactile measuring arm. The data were compared with the measurement data from the manufacturing of the octants. An "as-is" data set for the fasteners was created considering also the assembly inaccuracy of the vacuum vessel of ASDEX Upgrade. Based on this data set, the fastening points were adjusted in the test stand. Since the beginning of 2020, the parts of the new upper divertor have been installed. For future projects that are not yet known, the new system guarantees maximum flexibility – another investment requirement of IPP.

Heavy-duty stage for a standard SEM. The gear wheel does not belong to the stage. It represents a sample of about ten kilograms that is to be examined in the microscope (picture on the right).

Photo: IPP, Martin Balden

Photos: Kammrath & Weiss GmbH

Kammrath & Weiss GmbH, Schwerte, Germany
Carl Zeiss Industrielle Messtechnik GmbH, Oberkochen, Germany

Scanning electron microscopes (SEMs) allow analysis of sample surface morphology with nanometre-scale resolution. A typical application at IPP is the investigation of plasma-exposed components. Material scientists wish to inspect exactly the same spot – before and after exposure. This requires that the components, such as a divertor tile from the ASDEX Upgrade fusion research facility or a component with soldered water connections be mounted and traversed in the microscope. For this purpose, IPP acquired an SEM from Zeiss with a custom high-load sample stage. Furthermore, an integrated focused ion beam can be used to prepare cross-sections on a micrometre scale.

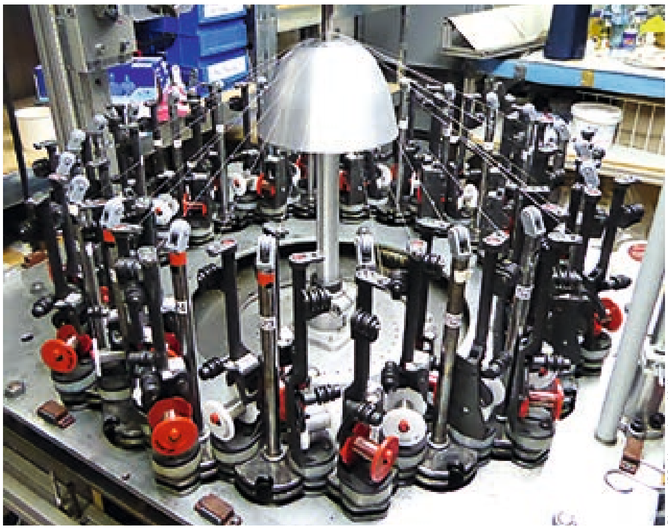
The sample stage must position a divertor tile (230 x 105 square millimetres) with an accuracy of five micrometres, even when tilted; the drift should be less than 100 nanometres over five minutes. At a maximum load of ten kilograms, an image resolution better than ten nanometres must be achieved. Other specifications for the custom stage, which Kammrath & Weiss GmbH manufactured on behalf of Zeiss, were a tilt range from -15 to +70 degrees, rotation through 360 degrees, and a vertical motion range of 100 millimetres.

Photo: Kammrath & Weiss GmbH

A first class accessory
Heavy-duty stage for scanning electron microscope

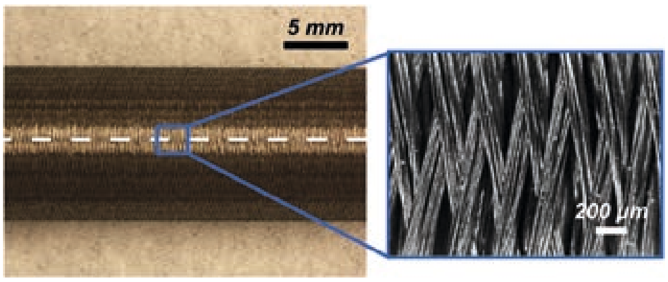
No SEM manufacturer offers a standard stage that can move a sample with a weight of ten kilograms and a length of up to 230 millimetres under the electron and ion beam to work in the micrometre or nanometre range. High positional accuracy, low drift, and low vibration – Kammrath & Weiss GmbH, experts for special microscopy solutions, were challenged to meet unprecedented requirements. "With the successful implementation of the stage, we have gained a lot of experience in the mechanical construction and the control of the stage," the company concludes. "For us, it's a reference project because we were able to show what is possible with a standard SEM when we refine it with our product."

TEC-KNIT CreativCenter für Technische Textilien GmbH, Rhede, Germany
Deutsche Institute für Textil- und Faserforschung, Denkendorf, Germany


Photos: IPP, Alexander v. Müller

Production of a braid from tungsten wire

Both the TEC-KNIT CreativCenter für Technische Textilien GmbH and the Deutsche Institute für Textil- und Faserforschung have, as contracting parties, developed new expertise regarding the processing of fine metal wires and could expand their portfolios accordingly. This now enables these contractors to acquire further orders in this field and to incorporate the new knowledge into the development of products for other applications as well.



Tungsten yarn braid; the individual filaments have a diameter of just 20 micrometres

At certain locations in the plasma vessel of a future fusion power plant where the hot plasma, held in magnetic suspension in front of the walls, comes into contact with the vessel, wall components must be able to withstand high thermomechanical loads. For the design of such components, high-performing and damage-tolerant high-temperature materials are required. Against this background, metallic composites reinforced by fine tungsten wires are currently considered as promising materials. However, in order to be able to manufacture components from such composites, the tungsten wires must first be processed into suitable preforms, e.g. woven or braided fabrics. The flexibility of thin tungsten fibres makes it possible to use textile technological processes for this purpose.

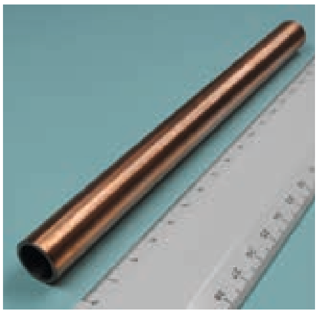
TEC-KNIT CreativCenter für Technische Textilien GmbH does not actually develop yarns, but highly functional textiles. Nevertheless, TEC-KNIT produced tungsten wire preforms for IPP by using a laboratory system for yarn production to successfully produce super-thin tungsten wires with a diameter of just 20 micrometres. These multifilaments were then further processed to preforms suitable for composite material fabrication by the Deutsche Institute für Textil- und Faserforschung. In particular, circular braiding was successfully applied to tungsten wires and yarns in order to produce tubular preforms for cooling pipes that can be used in components that are exposed to high heat loads.

Fine but strong! Preforms from thin, high-strength tungsten wires for high-performance composite materials

Louis Renner GmbH, Bergkirchen, Germany

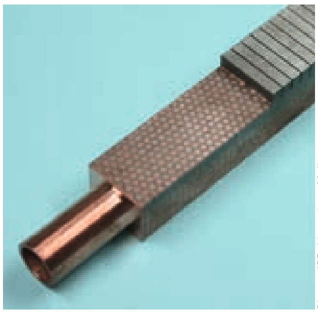
In highly loaded regions of the plasma vessel, wall components in a fusion power plant must withstand bombardment by fast plasma particles and the corresponding high heat fluxes. Such components are designed for steady-state heat flux loads of up to 20 million watts per square metre. Since tungsten, the currently preferred plasma-facing material, cannot be used as a structural material in such components due to its inherent brittleness, copper-based materials are used for this purpose. This is mainly due to the good ductility as well as the high thermal conductivity of copper-based materials. However, structural materials in wall components of fusion power plants must also exhibit an exceptional high-temperature strength. With this in mind, metallic tungsten-copper composites are currently considered as promising materials for this application. Due to their mutual insolubility, such materials can be fabricated by means of liquid copper melt infiltration of open-porous tungsten bodies. In this process, copper heated beyond its melting point creeps into the porous tungsten structure and fills the voids.

As part of the contract between IPP and the Louis Renner GmbH, the industrial-scale production of various tungsten-copper composite materials was tested. In addition, component mock-ups were manufactured that could be subjected to high-heat-flux tests at relevant loads. The results of these high-heat-flux tests verify the high performance of the tungsten-copper composites for applications in components exposed to high thermal loads.



Tube made of tungsten fibre-reinforced copper composite material, which was manufactured by means of copper melt infiltration of a tungsten fibre braid.

Mock-up of a plasma-facing component with a heat sink made of tungsten particle-reinforced copper composite material



Photos: IPP, Alexander v. Müller

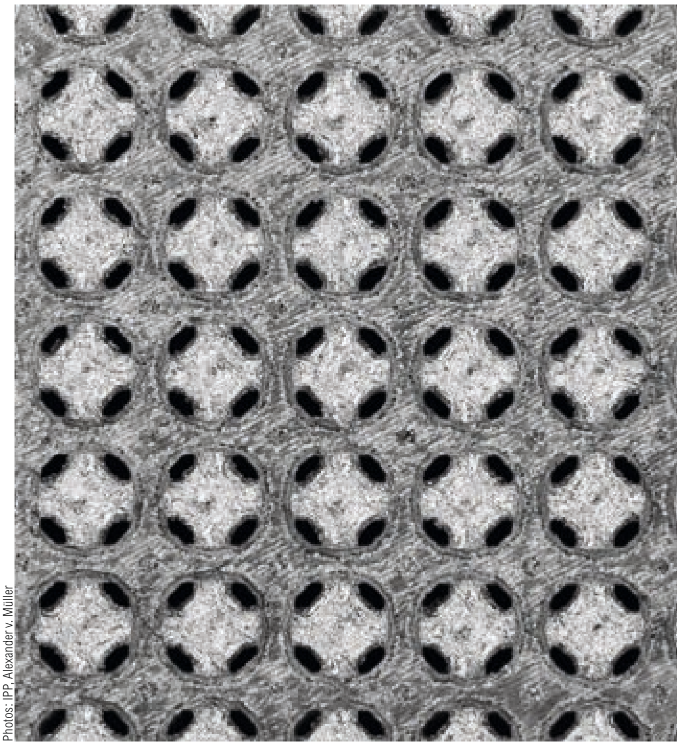
Mock-up of a plasma-facing component with a heat sink based on a copper-infiltrated tungsten honeycomb structure

And the Innovation Award goes to… Tungsten-copper composites for high-heat flux applications

As a manufacturer of refractory and composite metal products, the Louis Renner GmbH has been able to develop knowhow with which existing manufacturing processes and products could be optimised in terms of purity and material properties. The composite materials that were fabricated by Louis Renner GmbH for IPP go in many respects beyond the current industrial state-of-the-art, which is why new applications may arise for such materials in the future.

In 2019, the Innovation Prize of the German Copper Institute was awarded to an IPP scientist for his development work on tungsten-copper composites. The prize committee recognised that the work carried out at IPP “represents a pioneering contribution to the development of innovative products made of copper and copper alloys”. The annual Innovation Award of the German Copper Institute is a funding competition for students, doctoral candidates and scientific staff from all areas of engineering and natural science in research and industry. Independent jurors from the copper-processing industry and academia evaluate the submitted papers. The German Copper Institute, a technical-scientific professional association, was founded in 1927; at present, it is maintained by 26 member companies.

Hot off the 3D printer
Additive manufacturing of tungsten by means of selective laser beam melting



Photos: IPP, Alexander v. Müller

Microscopic top view on an additively manufactured lattice structure made of tungsten

Additively manufactured tungsten parts after the manufacturing process when being removed from the powder bed.

Processing tungsten and other refractory metals using additive manufacturing processes has become a core competence at Fraunhofer IGCV. The processing of tungsten by means of laser beam melting is associated with a number of hurdles, which were identified and largely overcome in the course of the collaboration. Due to the high material density and the possibility of creating complex geometries, a very interesting field of application opens up in the area of radiation optics for imaging techniques in medical devices. Fraunhofer IGCV has already been able to establish new partnerships in this field. Another promising application lies in the area of space propulsion.

Photos: IGCV, Maximilian Binder

Preheated tungsten build platform during the additive manufacturing process

Fraunhofer-Institut für Gießerei-, Composite- und Verarbeitungstechnik, Augsburg, Germany

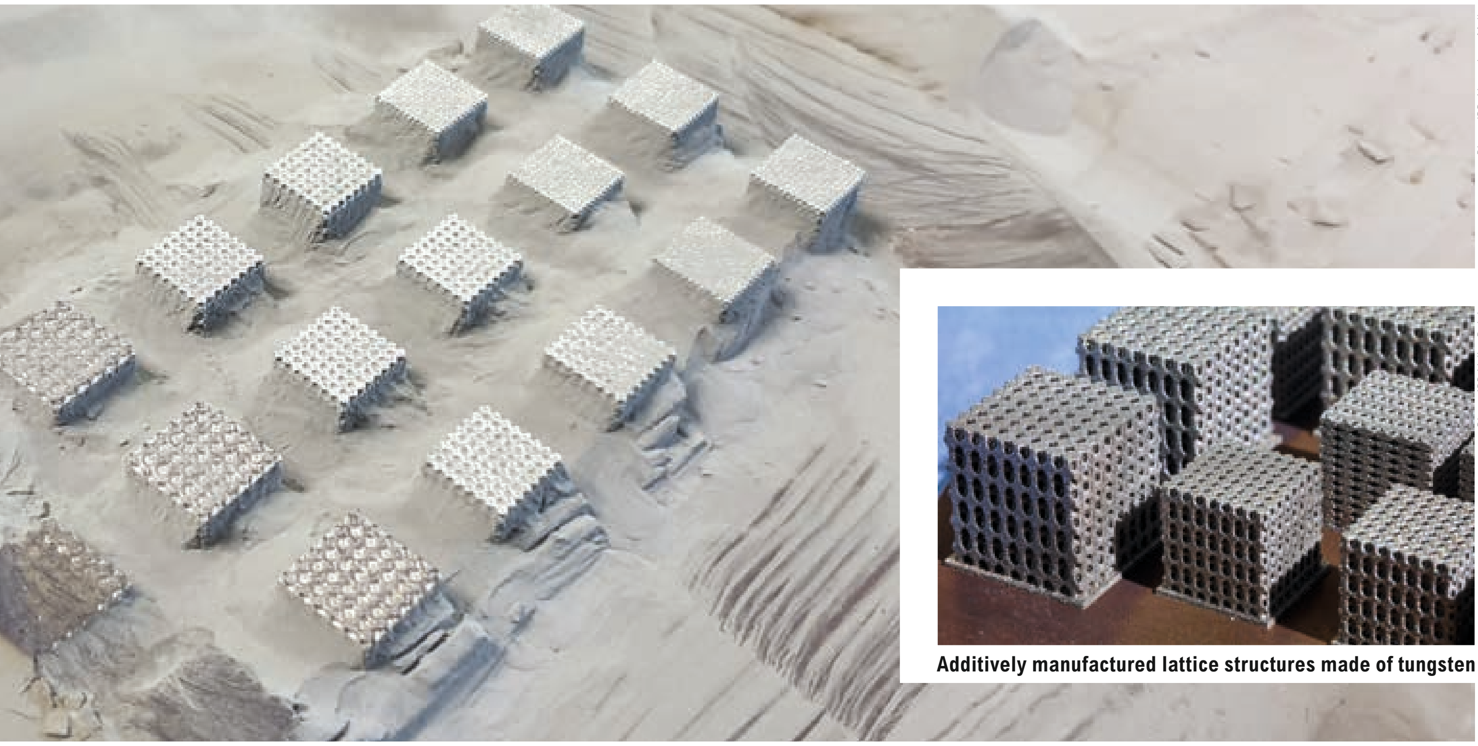


Photo: IPP, Alexander v. Müller

Photo: IPP, Volker Rohde

Additively manufactured lattice structures made of tungsten

Tungsten, the metal with the highest melting point, is currently the favoured plasma-facing material for wall components in magnetic confinement fusion devices. This is mainly due to the robustness and erosion resistance of tungsten under plasma exposure. However, tungsten is also a very hard and intrinsically brittle metal. Therefore, it is relatively difficult to manufacture and machine components from tungsten, which in turn implies constraints and limitations on the design of tungsten components. Novel and innovative processes using additive manufacturing ("3D printing") of metals open up entirely new possibilities in terms of design freedom. Considering this, additive manufacturing of tungsten bears considerable potential, not only for fusion technology, but also for numerous applications that could benefit from the outstanding properties of the refractory metal tungsten – or which could only become possible through it in the first place.

As a contracting partner of IPP, the Fraunhofer-Institut für Gießerei-, Composite- und Verarbeitungstechnik (IGCV) identified parameters for the consolidation of tungsten through selective laser beam melting on various laser beam melting systems. The institute furthermore invested in special equipment that allows the realisation of high preheating temperatures and thus the "printing" of metals that tend to be brittle, such as tungsten, with high material quality. Apart from that, the fabrication of complex tungsten structures was demonstrated, such as fine lattice structures, which are of particular interest for plasma-facing components in fusion devices.

Brittleness passé! Tungsten-fibre-reinforced tungsten

Photo: IPP

Cross-section of tungsten-fibre-reinforced tungsten composite: The material was manufactured by a newly developed technique: chemical vapour infiltration of tungsten. The circular structures with diameters of about 150 µm are cross-sections of the tungsten fibres.

Photo: IPP, Martin Balden

View through an electron microscope: tungsten-fibre-reinforced tungsten after a destructive test – winning photo in the "NuMart Image Competition". The composite material developed at IPP exhibits an enhanced fracture toughness.

Osram GmbH, Schwabmünchen, Germany Archer Technicoat Ltd., High Wycombe, United Kingdom

With its unique combination of material properties, tungsten is a promising candidate for wall components directly facing the plasma in a future fusion power plant. One drawback, however, is the brittleness of the material, as it becomes susceptible to damage and cracks when subjected to mechanical loading – a problem that significantly limits its use. One possible solution is to create structures inside the tungsten that can distribute local stresses and thus provide a kind of toughness, i.e. an improved resistance to failure. Such an externally introduced toughness enhancement or "pseudo-ductility" can be achieved by, for instance, embedded fibres, which can bridge and deflect developing cracks or can deform plastically. Ceramic-fibre-reinforced ceramics are an example of successful implementation of this concept. In the context of research work at IPP, this idea was applied to tungsten. The metal is reinforced with coated high-strength, ductile tungsten fibres, which creates a tough composite material.

IPP involved Osram GmbH as a manufacturer of tungsten wires in the development work to optimise the properties and effects of the wires used in the composite material. In addition, IPP commissioned Archer Technicoat Ltd. to test a manufacturing process using chemical vapour infiltration (CVI), with which larger and more reproducible quantities of the composite material can be produced. In a follow-up project, Archer Technicoat Ltd. delivered its first commercial CVI facility for tungsten to Forschungszentrum Jülich.

The collaboration between IPP and the Osram GmbH has contributed to improving the performance of the tungsten wire material. This opens up new business fields for Osram GmbH beyond existing areas of high-temperature applications. High-strength, ductile tungsten wires have recently shown to be promising not only as fibres for composite materials in fusion research, but are also of great interest with respect to other high-tech applications with extreme requirements. Additionally, Archer Technicoat Ltd. was able to develop expertise regarding the vapour deposition of tungsten on coated tungsten fibres and fabrics. This has also enabled this company to expand its portfolio. In the meantime, Archer Technicoat Ltd. has acquired and carried out further projects with various partners on the subject of CVI of porous tungsten substrates.

Imprint

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MAX PLANCK GESELLSCHAFT

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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