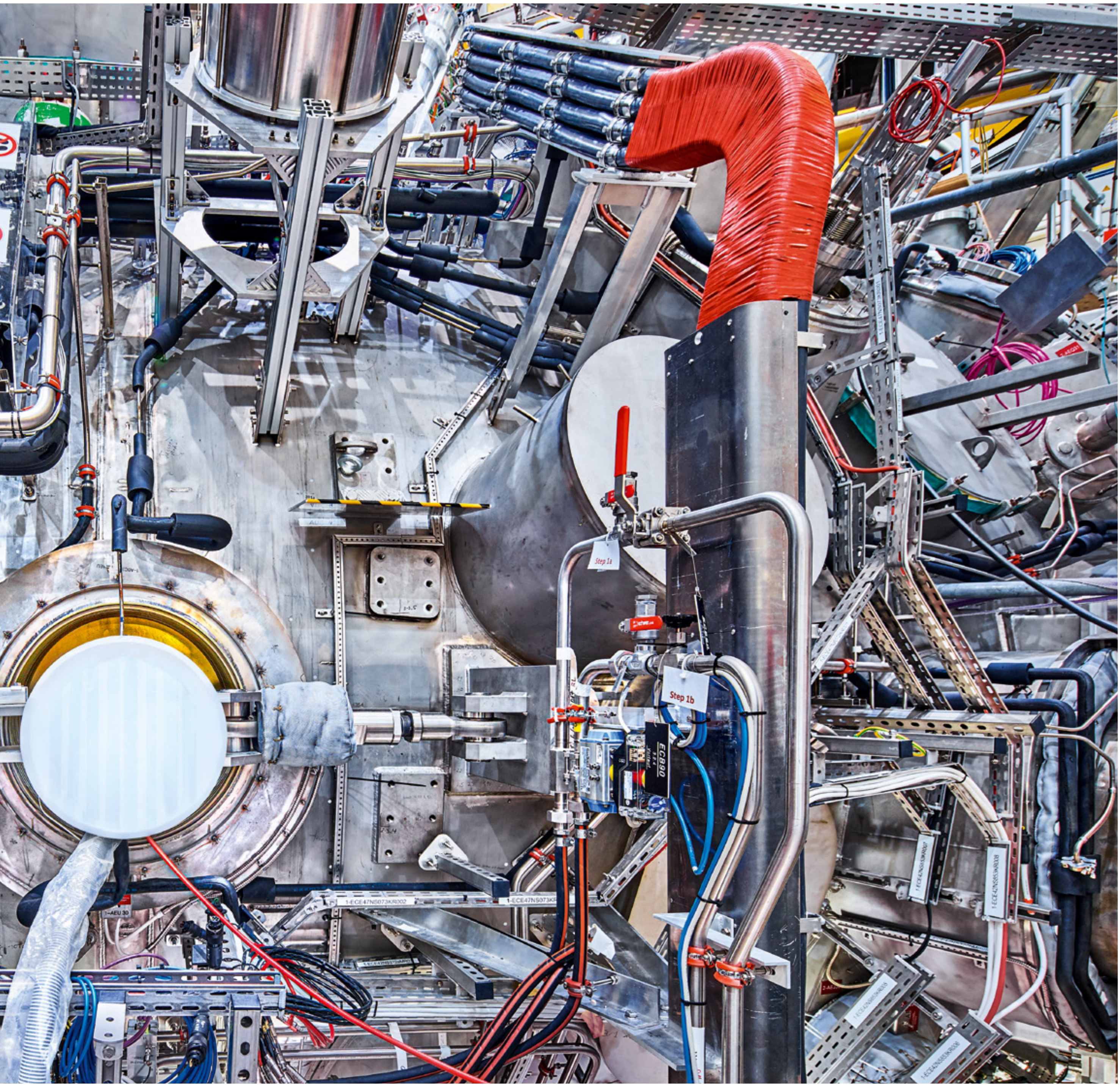
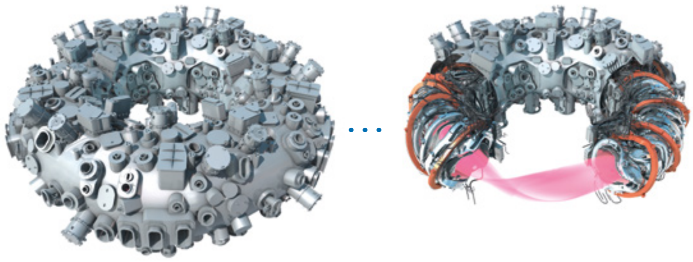
Max-Planck-Institut für Plasmaphysik

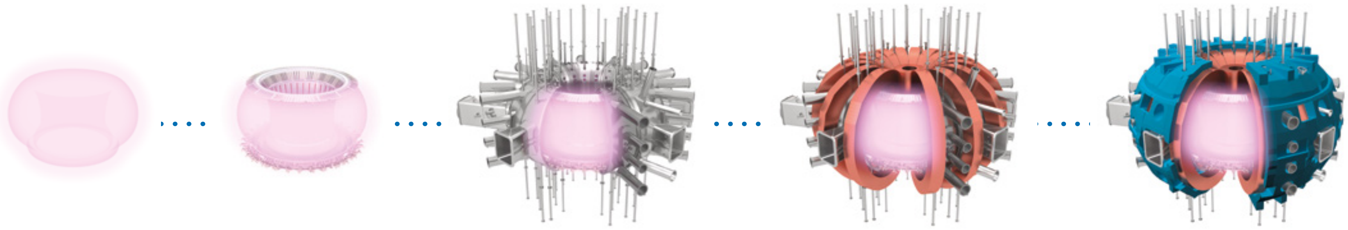


IPP & Industry

At the cutting edge of technology

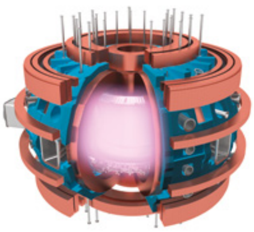
Wendelstein 7-X





At the cutting edge of technology

How can industrial companies benefit from fusion research contracts?



ASDEX Upgrade

Fusion lights up sun and stars. If we succeed in utilising this energy source on earth, humanity will be guaranteed an important contribution to a long-term supply of power and heat. Scientists around the world are working on complex technologies for future fusion power plants – and Max Planck Institute for Plasma Physics (IPP) is participating with a leading role. It is the only institute in the world to investigate both types of fusion devices – tokamak and stellarator – in parallel: in Garching it operates the ASDEX Upgrade tokamak and in Greifswald the still young Wendelstein 7-X stellarator. Ultra-thin but extremely hot is the plasma, an electrically charged hydrogen gas that is studied in these research facilities. To be able to heat it to an ignition temperature of more than 100 million degrees Celsius, it has to be contained in a magnetic field cage.

Building and enhancing a fusion research facility – this is a technological and scientific challenge that has almost reached the limits of what is achievable technically. More than off-the-shelf solutions have to be sought and found, jointly tested and practiced. Industrial partners are driven to technological excellence, as the following success stories, especially from the construction phase of Wendelstein 7-X, demonstrate. This creates added value, especially for the companies: Often they can subsequently increase their competitiveness and expand their portfolio through the newly acquired know-how.

How do industrial companies benefit from contracts for fusion research? We would like to thank our partners from industry who have provided us with information for the revised and extended edition of this brochure.

Wendelstein 7-X

Companies from all over Europe have worked closely with the Max Planck Institute for Plasma Physics (IPP) in developing and manufacturing the Wendelstein 7-X fusion research device. This process has given rise to many demanding challenges and provided the participating companies with valuable technological expertise. The following pages will describe a few of these achievements.

Wendelstein 7-X is the world's largest fusion device of the stellarator type. Its objective is to investigate the suitability of this type for a power plant. Discharges of up to 30 minutes will demonstrate its essential property, namely, that of continuous operation.

A key part of the experiment is the coil system, which consists of 50 non-planar and 20 planar superconducting magnetic coils. They create magnetic fields, which confine the hydrogen plasma at temperatures up to 100 million degrees, so that it can be investigated with various techniques. In the magnetic coils a superconducting niobium-titanium conductor is used rather than a normally conducting copper material. During the experiment, liquid helium flows through the coils to cool them down to temperatures of approximately -270 degrees Celsius, close to absolute zero. Due to this low operating temperature, the coils have been installed in a cryostat that is made up of a plasma vessel and an outer vessel. The vacuum generated between the two vessels insulates the coils from ambient heat.

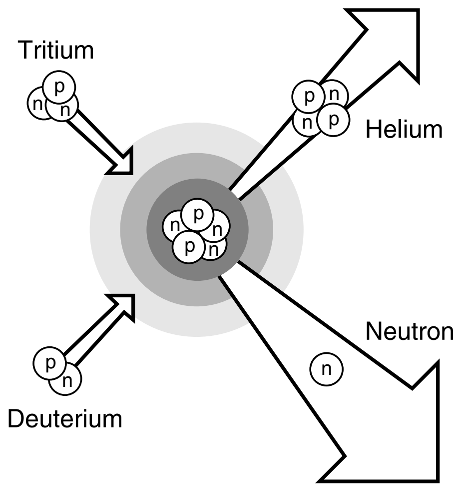
The plasma can be investigated and heated using the 254 ports. Three different methods are used for heating the plasma: microwave heating with a power of ten megawatts, radio wave heating with four megawatts and neutral beam injection heating with 20 megawatts.

Five almost identically built modules constitute the Wendelstein 7-X device. Each module consists of a part of the plasma vessel, its thermal insulation, ten superconducting stellarator coils, and four planar coils, as well as the pipe system for cooling the coils, a segment of the supporting central ring and the outer vessel. In December 2015, Wendelstein 7-X was launched after nine years of construction and over one million assembly hours. It is being further upgraded step by step.

ASDEX Upgrade

The ASDEX Upgrade tokamak, which has been in operation since 1991, is investigating all key issues relating to the tokamak type of a future fusion power plant. ASDEX stands for "Axially-Symmetric Divertor Experiment". It is named after the divertor, a special magnetic field configuration. It allows the interaction between the hot fuel and the surrounding walls to be controlled. Its tungsten wall cladding, which is suitable for use in power plants, and its flexible, powerful plasma heating makes ASDEX Upgrade one of the world's most important tokamaks. It is preparing for the ITER international large-scale experimental reactor, which is currently being built in southern France in a worldwide collaboration. ITER is to show that energy can be derived from nuclear fusion.

To solve new challenges the ASDEX Upgrade team also regularly works with partners from industry.



Nuclear fusion reaction scheme: IPP

Hydrogen nuclei fuse in the sun and stars under enormous gravitational pressure. A fusion power plant on earth, however, must operate on another principle. Under terrestrial conditions it is the two types of hydrogen, deuterium and tritium, which react most easily. They form a helium nucleus; a neutron is also released and huge amounts of usable energy are generated. In a power plant, one gram of fuel can generate 90,000 kilowatt-hours of energy. This corresponds to the heat of combustion of eleven tons of coal.

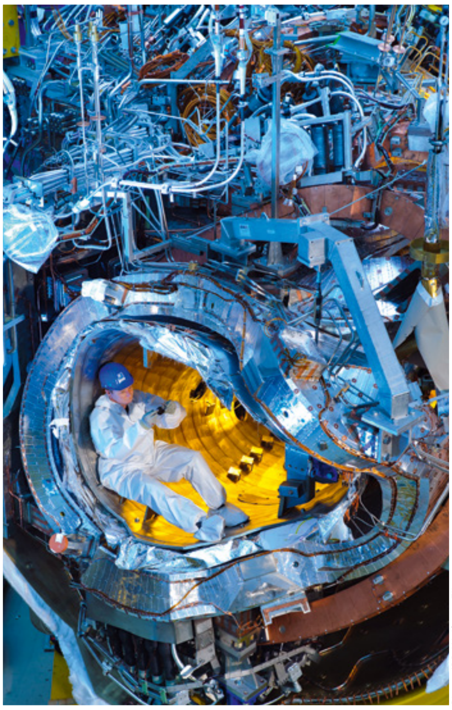


Photo: IPP, Wolfgang Filser

Wendelstein 7-X during assembly

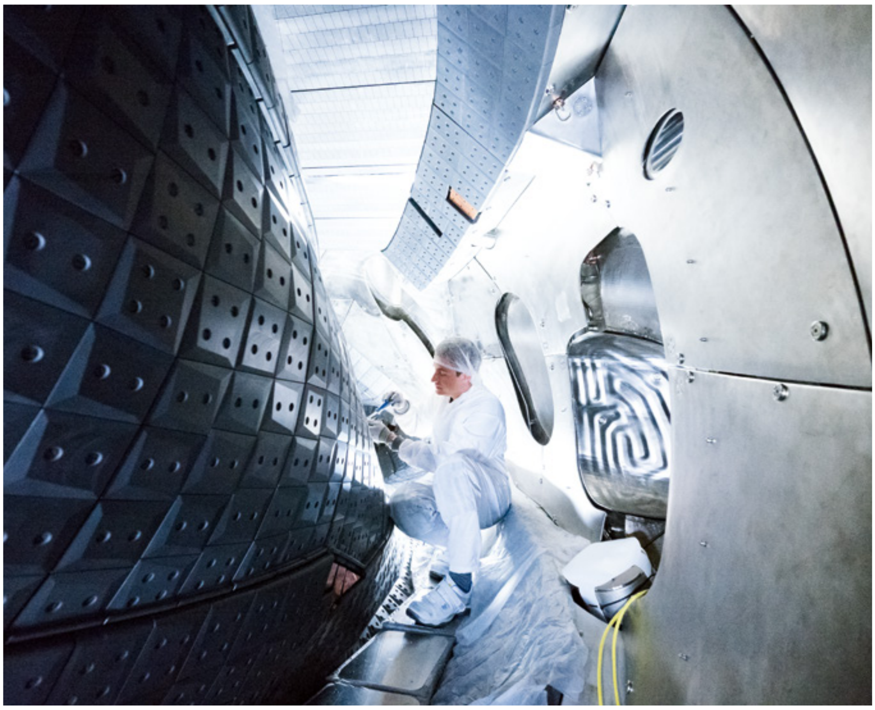


Photo: IPP, Jan Hosan

In the plasma vessel of Wendelstein 7-X

ASDEX Upgrade

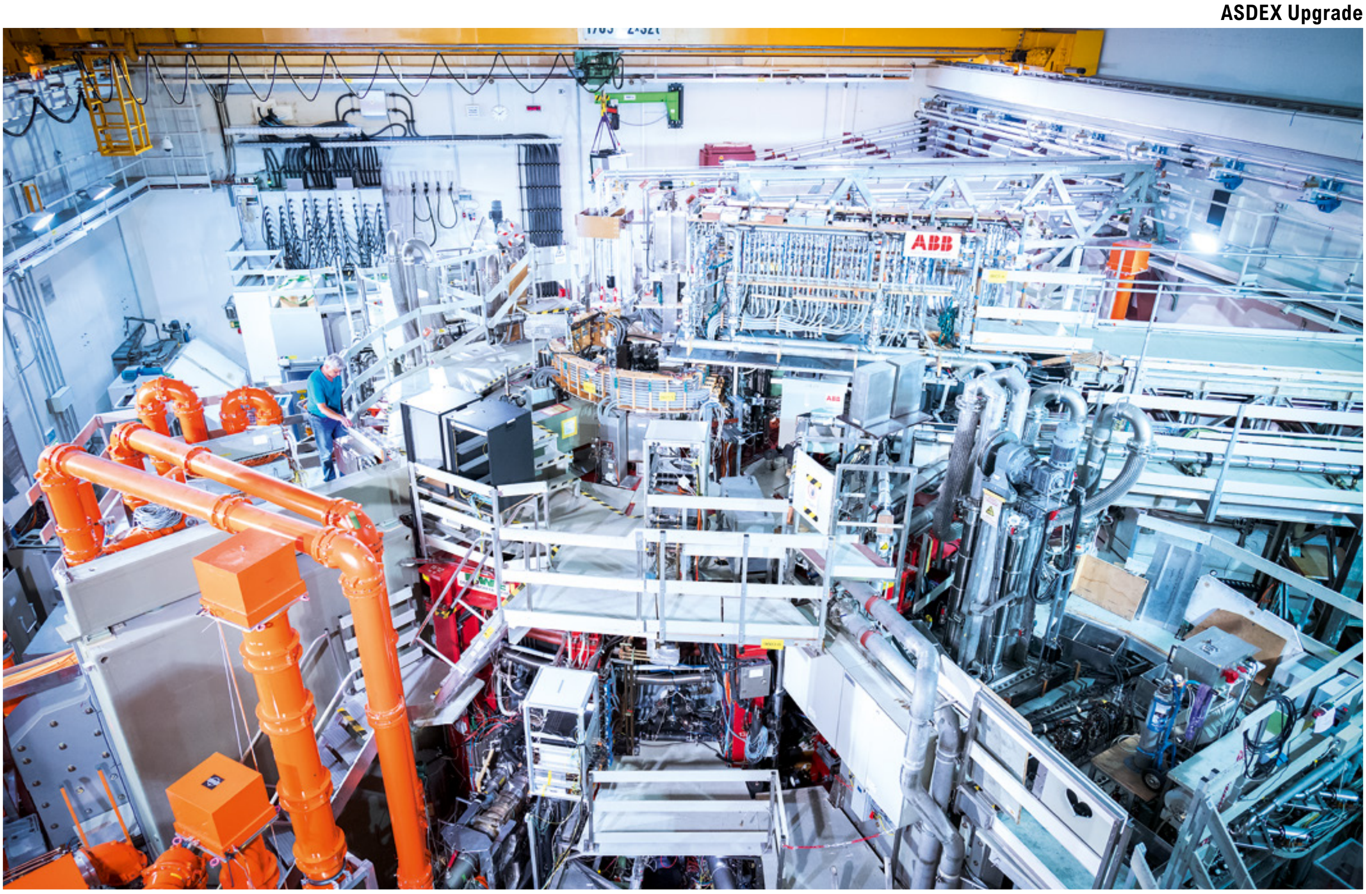


Photo: IPP, Jan Hosan

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.

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

Photo: IPP, Wolfgang Filser

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
Element Six Ltd., London, Great Britain
Diamond Materials GmbH, Freiburg, Germany
Reuter Technologie GmbH, Alzenau/Schöllkrippen, Germany

Ignition of a fusion reaction requires a heating system suitable for heating the plasma to 100 million degrees Celsius. Heating with microwaves has been considered a very interesting option. However, this technology requires the development and production of highly efficient microwave sources capable of generating 1 million watts. The initial results were achieved in Russia, the United States and Japan, when pulses of only a few seconds duration could be generated. The Wendelstein 7-X experiment requires, however, microwave tubes (or so-called ”gyrotrons”), which are capable of generating full power for 30 minutes. This is more than one hundred times the duration of the pulses already achieved and meant advancing into an entirely new technological dimension. This process was pushed forward by the close cooperation between Thales Electron Devices (TED), the Karlsruhe Institute for Technology and IPP. Currently, the three partners are working together on a research and development project to increase the heating power of the gyrotron to 1.5 megawatts.

The joint development of the original prototype was so successful that the batch production could be started without delay. However, the consortium was then faced with new problems that arose during manufacturing, thus creating new technical challenges. During batch production, the ceramic material used had to be replaced, which caused undesirable electromagnetic oscillations in the beam tunnel. To solve this problem, the Karlsruhe Institute of Technology suggested, and patented, a specifically calculated symmetry perturbation for the beam tunnel.

The heat absorbed by the collector material from the electron beam represents an additional problem. The vacuum could deteriorate due to the high local intermittent loads. The research institutes involved suggested distributing the heat emission over a broader area using temporally variable, externally generated magnetic fields. Thales Electron Devices successfully implemented this concept and made the breakthrough that improved the reliability of gyrotrons in continuous operation. A joint patent was issued for this technology. It can be applied to high-efficiency electron tubes and offers significant potential for improving high efficiency tubes in all fields of application.

Soldered diamond window using the CVD process in a diamond window

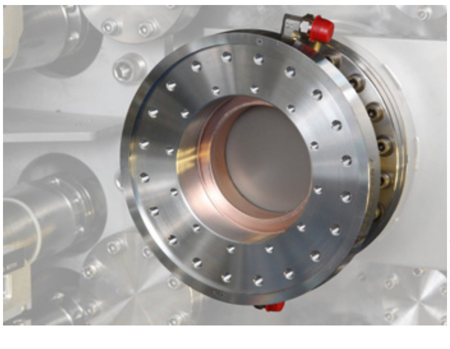


Photo: IPP, Tino Schulz

Photo: IPP, Wolfgang Filser

A diamond window to the plasma

Heating plasma for Wendelstein 7-X

The window between the tube and the exterior is another critical component of the gyrotron. It is made of artificial diamond with a high level of purity to ensure that the thermal losses will be kept as low as possible. These diamond windows, which have been manufactured by Diamond Materials and Element Six, in collaboration with the Karlsruhe Institute für Technologie, 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.

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 for Technology have developed their skills in soldering diamond and copper with special copper-silver-titanium solders. Soldering provides the basis for constructing a diamond window, which after further soldering is mounted in a stainless steel housing and used in a standard millimetre wavelength transfer line. Soldering together these two very different materials to produce a vacuum-tight seal represented a special challenge during the manufacture of the diamond windows with their integrated cooling.

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 10 microwave sources. Part of this project to increase the heating power at Wendelstein 7-X is a new industrial contract with Thales 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.

High-performance microwave tube for continuous operation

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.

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

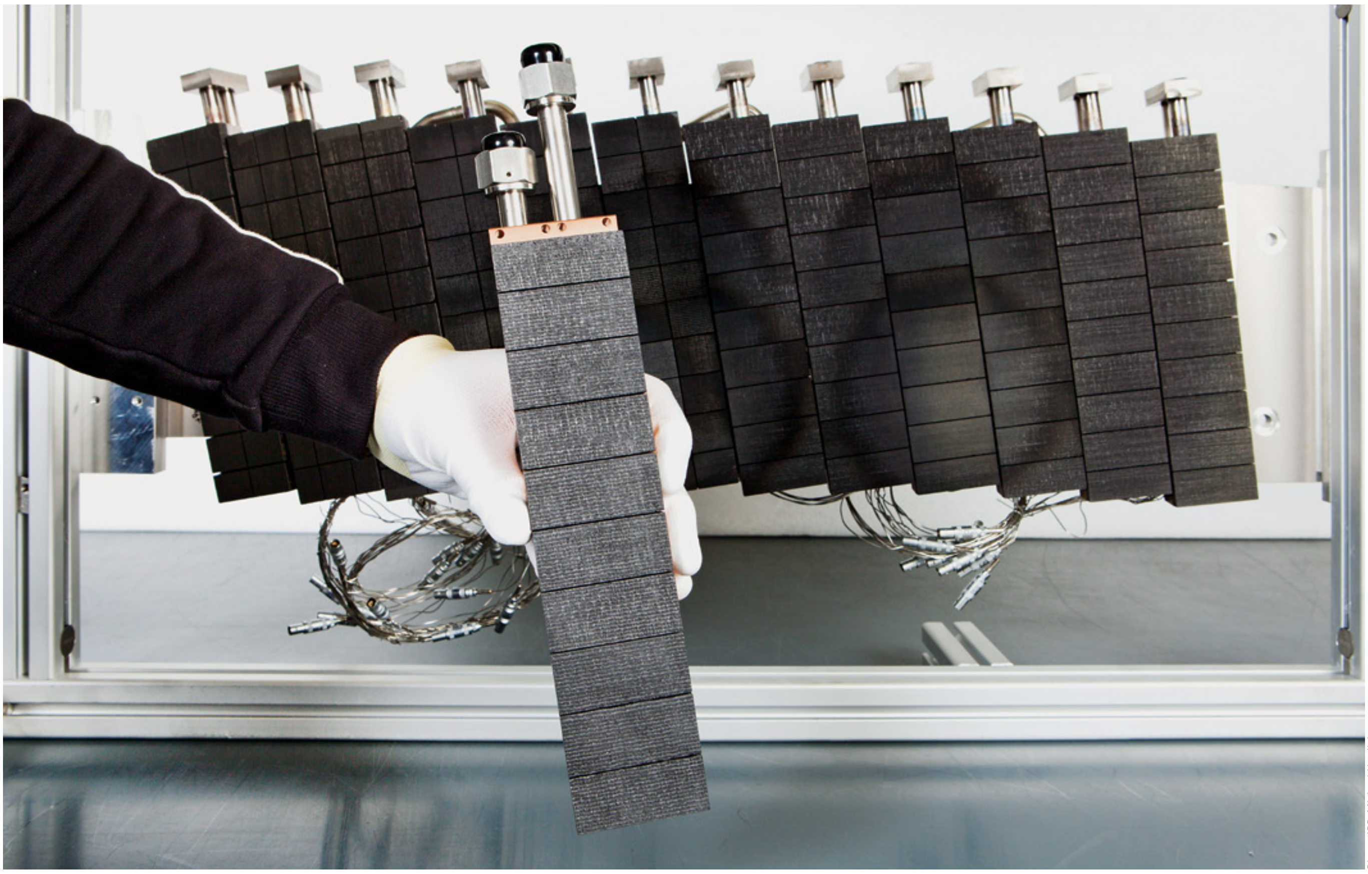


Photo: IPP, Michael Herdlein

▶ 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

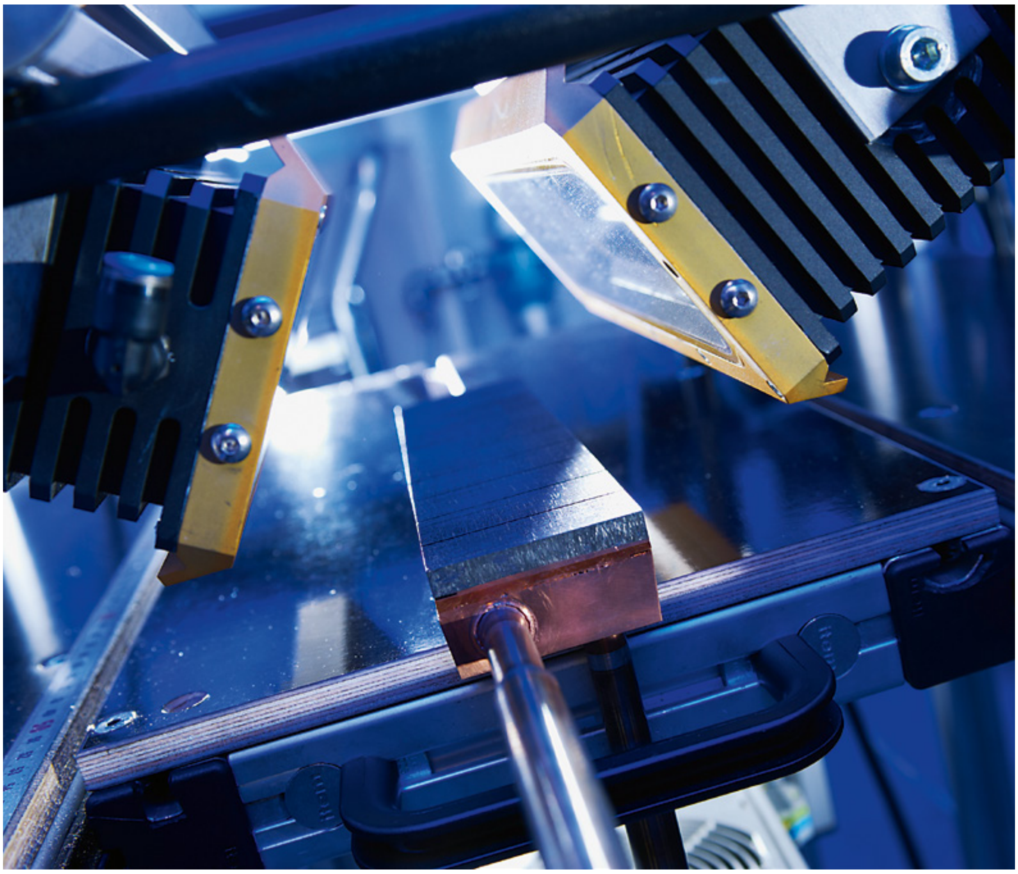


Photo: Plansee SE

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"**

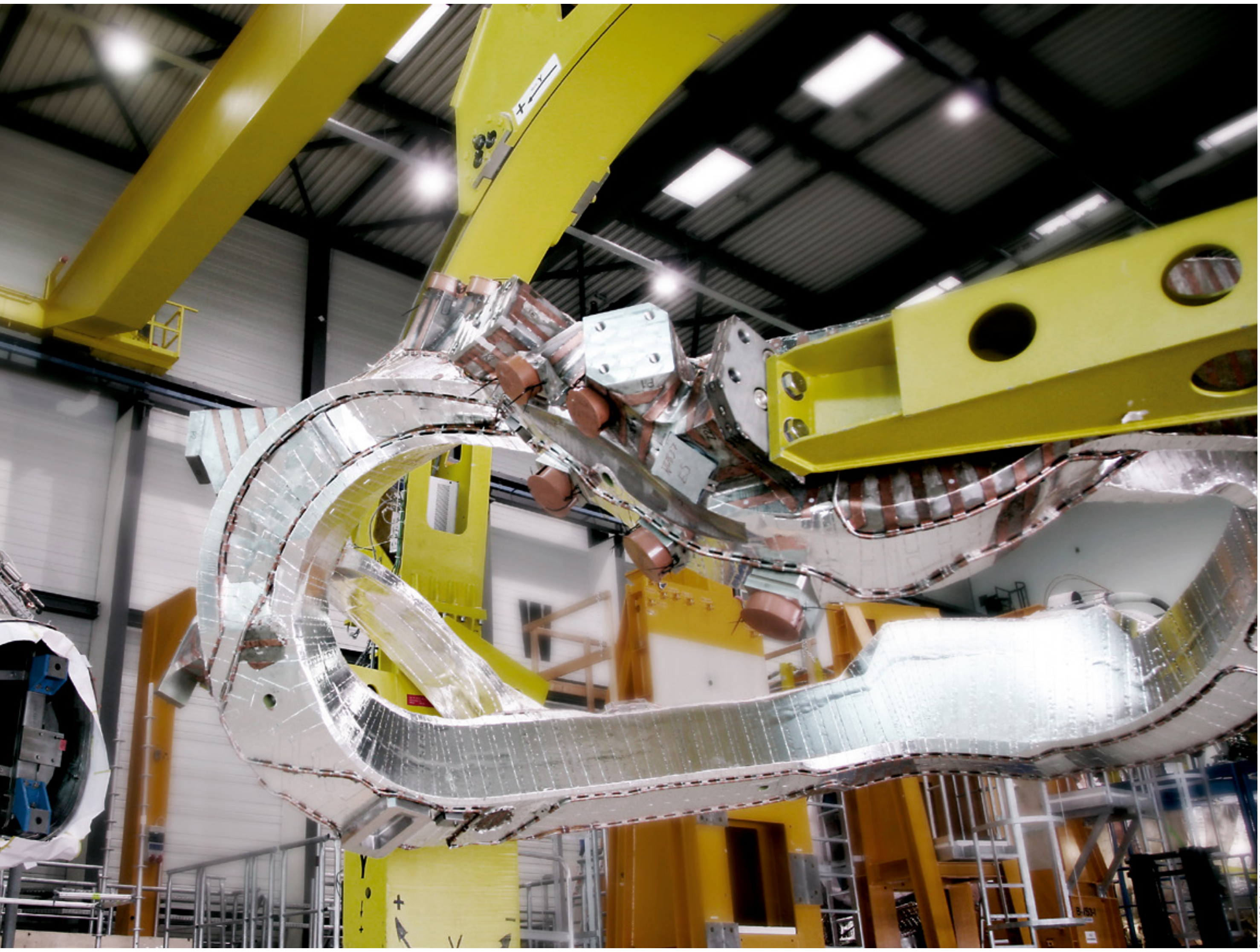


Photo: IPP, Anja Richter

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

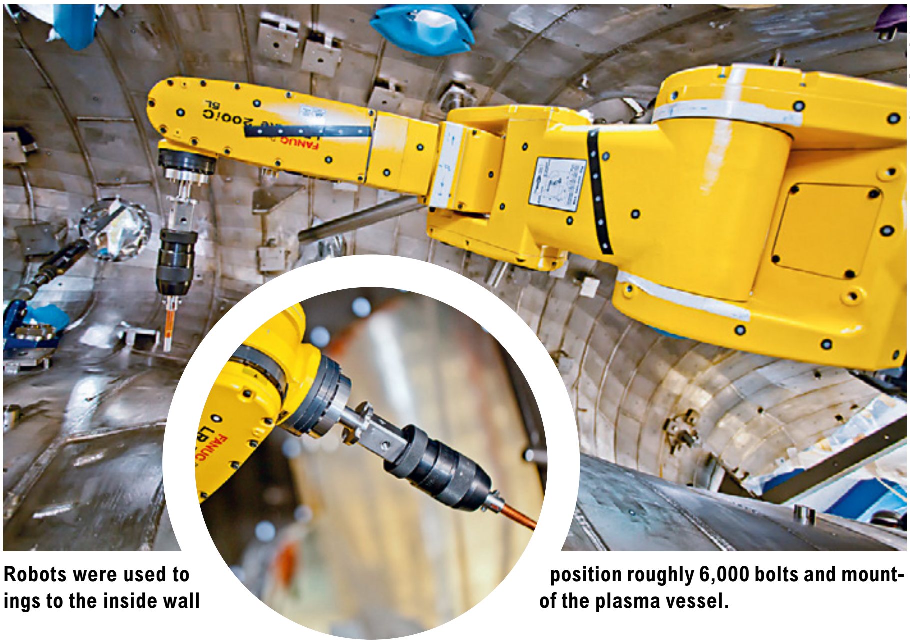
Cold, colder, Wendelstein 7-X – view into the refrigeration system

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.

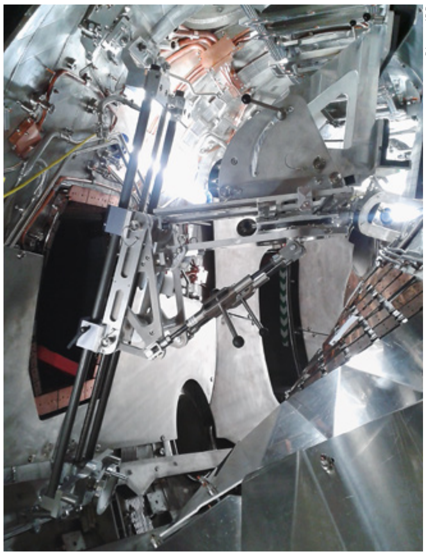


Photo: IPP

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

> 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.

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.

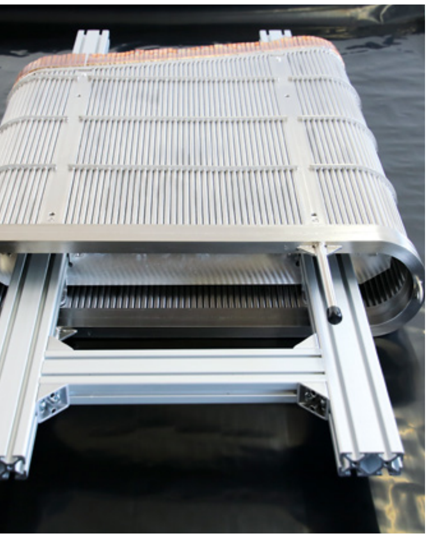
Safety and radiation tests ensure the protection of people and the environment from the harmful effects of ionising radiation.

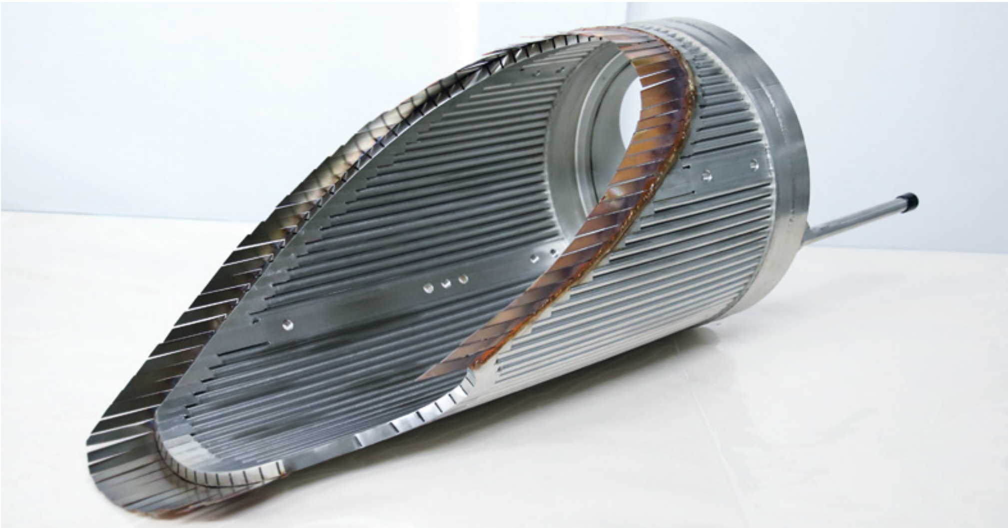
TÜV Rheinland, one of the world's leading independent testing service providers, has a wealth of experience in various applications of ionising radiation in research, medicine, technology, and energy generation. This experience allowed TÜV Rheinland to derive safety and radiation protection requirements 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.

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

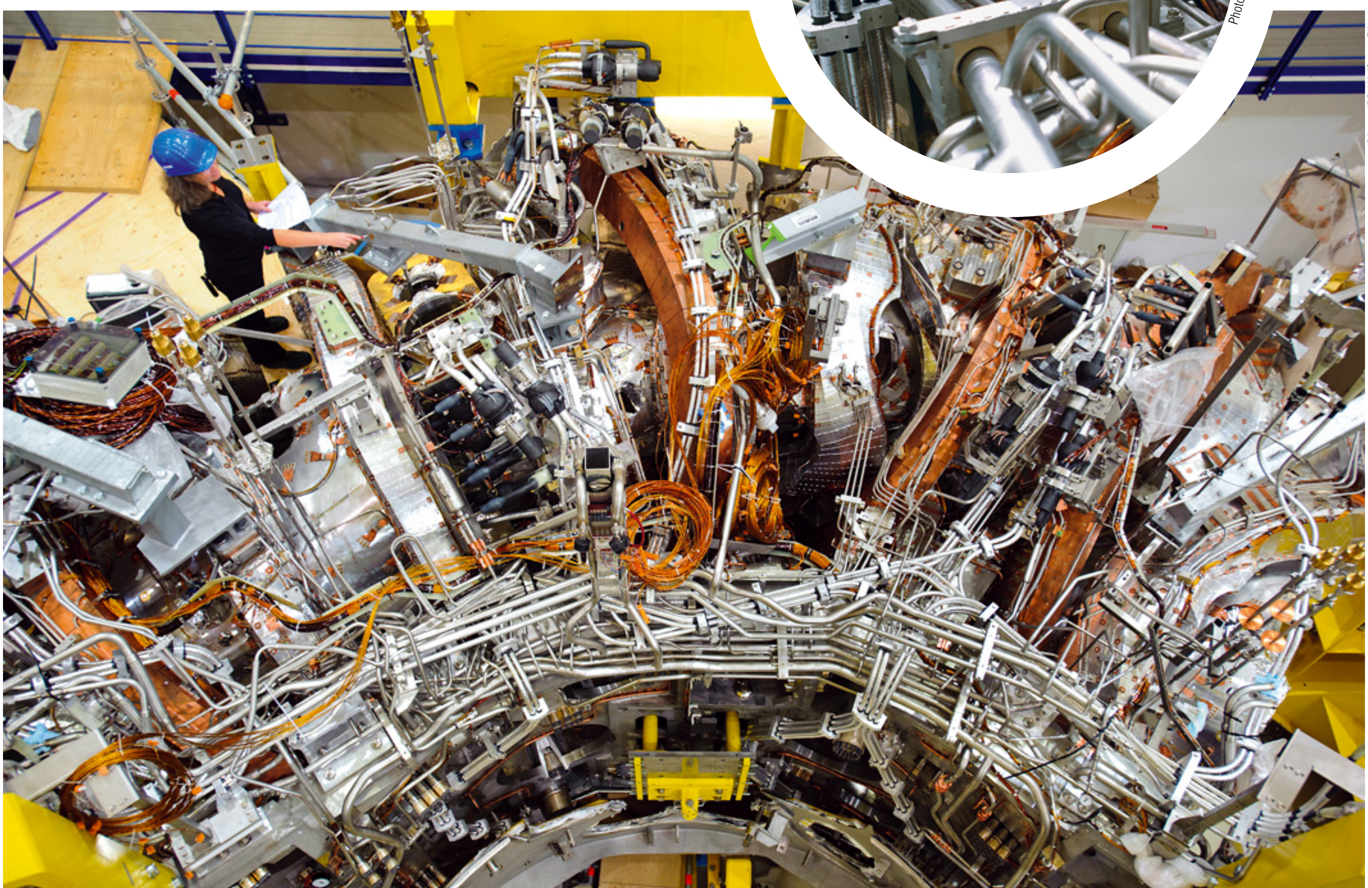


Photo: IPP, Wolfgang Filser

Micrometer precision work Mechanical machining of the central ring

CLP Srl, Borgo San Dalmazzo, Italy

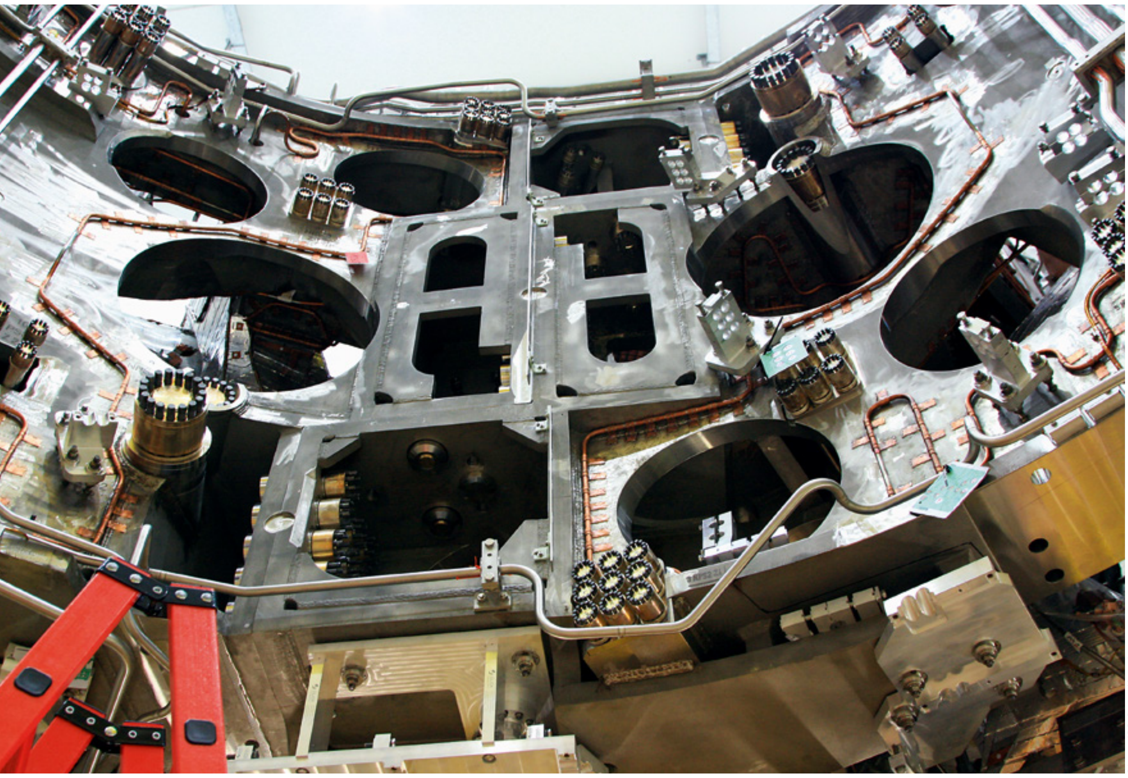


Photo: IPP, Beate Kemnitz

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.

Wendelstein 7-X central ring

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

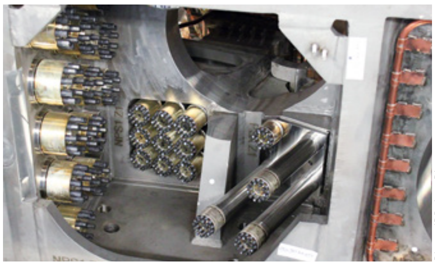


Photo: IPP, Jörg Riemann

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

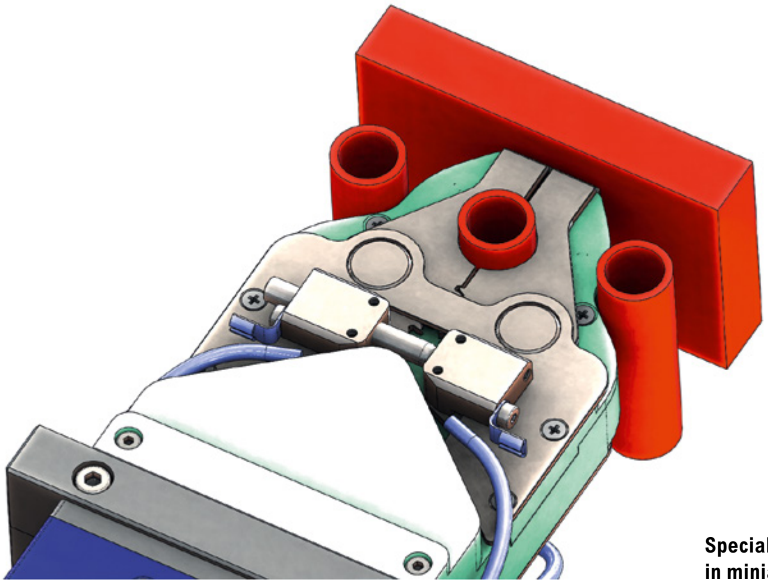
The 70 superconducting coils of Wendelstein 7-X must be electrically and hydraulically connected to each other as well as to the current leads. This is done by 124 three-dimensionally pre-formed superconductors. Thin filaments of the niobium-titanium superconductor are embedded in copper wires that are 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.



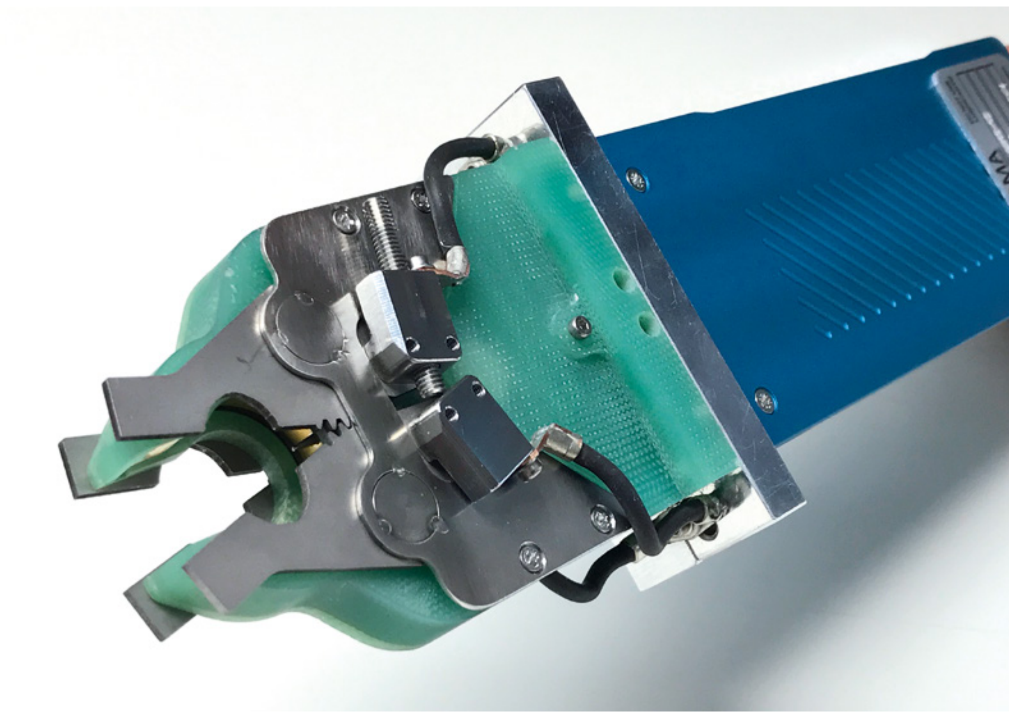
Special welding head in miniature format

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.

CAD and photo: Encoma GmbH



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

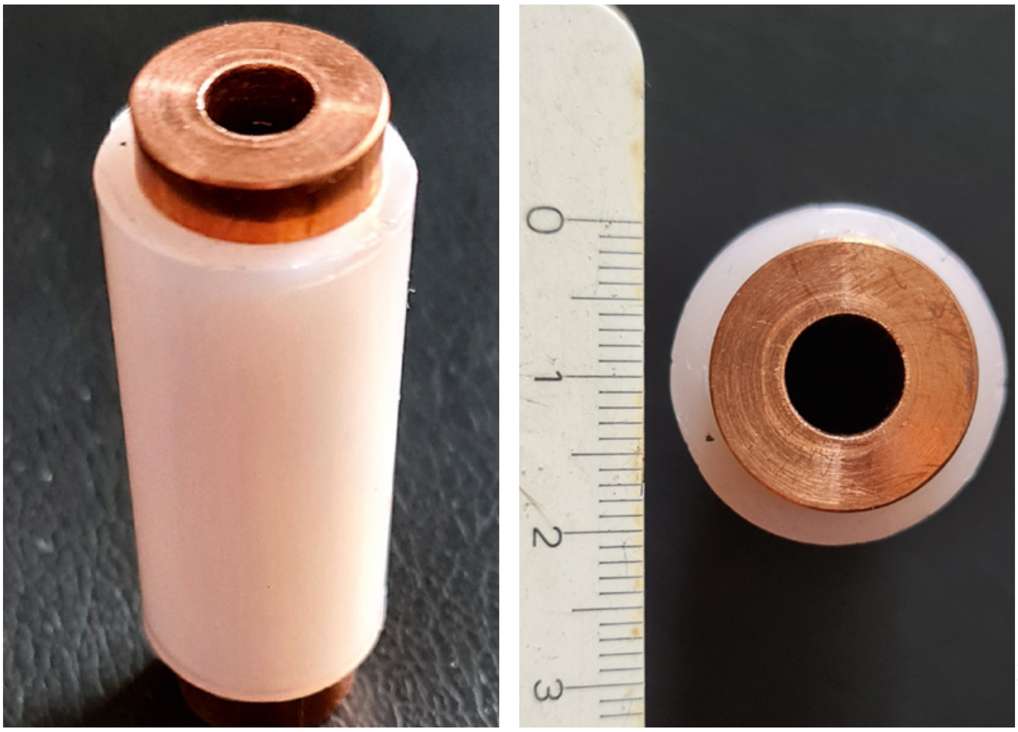
ASDEX Upgrade at the Max Planck Institute for Plasma Physics in Garching is the largest national tokamak fusion device in Europe. To control the interaction between the hot fusion plasma and the surrounding walls, ASDEX Upgrade is equipped with a particular component, a "divertor". It generates a special 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

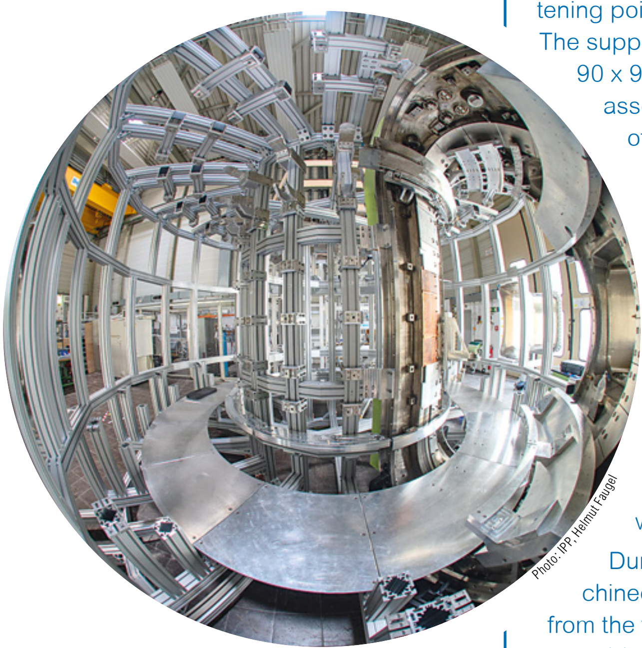
conductors with stainless-steel sheaths electrically insulated with ceramics (magnesium oxide), as required for the international experimental reactor ITER. However, the TIC conductor for ASDEX Upgrade has new requirements. Tefzel is to be used as the insulation material instead of ceramics because it 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).

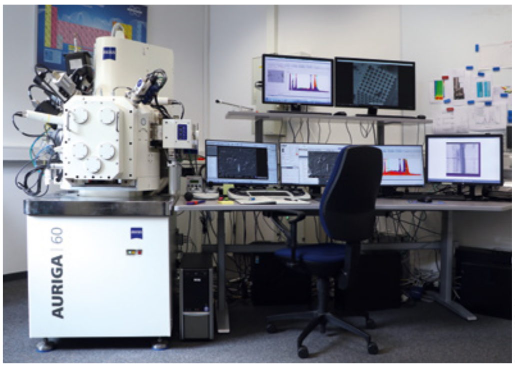


Photo: IPP, Martin Balden

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.

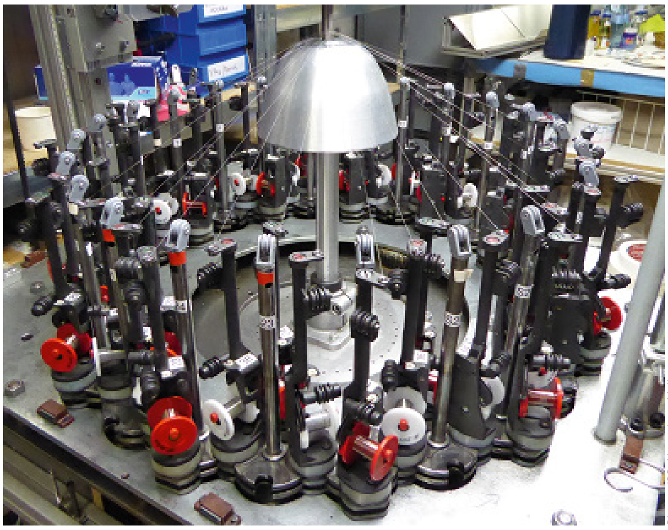
The sample stage must position a divertor tile (230 x 105 square millimetres) with an accuracy of five micrometres, even when tilted; the drift should be less than 100 nanometres over five minutes. At a maximum load of ten kilograms, an image resolution better than ten nanometres must be achieved. Other 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.”

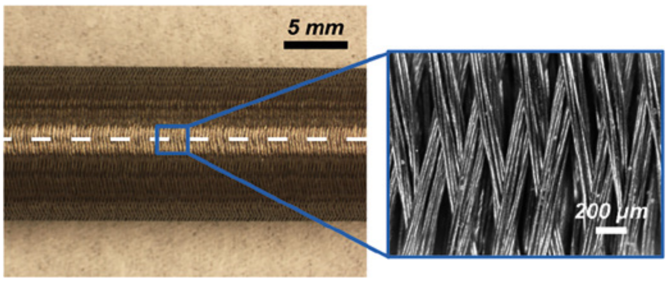
TEC-KNIT CreativCenter für Technische Textilien GmbH, Rhede, Germany
Deutsche Institute für Textil- und Faserforschung, Denkendorf, Germany



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.

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.



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

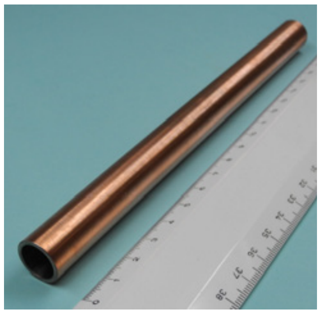
TEC-KNIT CreativCenter für Technische Textilien GmbH does not actually develop yarns, but highly functional textiles. Nevertheless, TEC-KNIT produced tungsten wire preforms for IPP by using a laboratory system for yarn production to successfully produce super-thin tungsten wires with a diameter of just 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

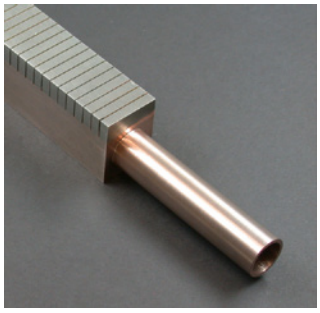
Louis Renner GmbH, Bergkirchen, Germany

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.

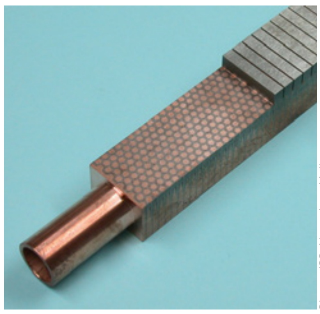
As part of the contract between IPP and the Louis Renner GmbH, the industrial-scale production of various tungsten-copper composite materials was tested. In addition, component mock-ups were manufactured that could be subjected to high-heat-flux tests at relevant loads. The results of these high-heat-flux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

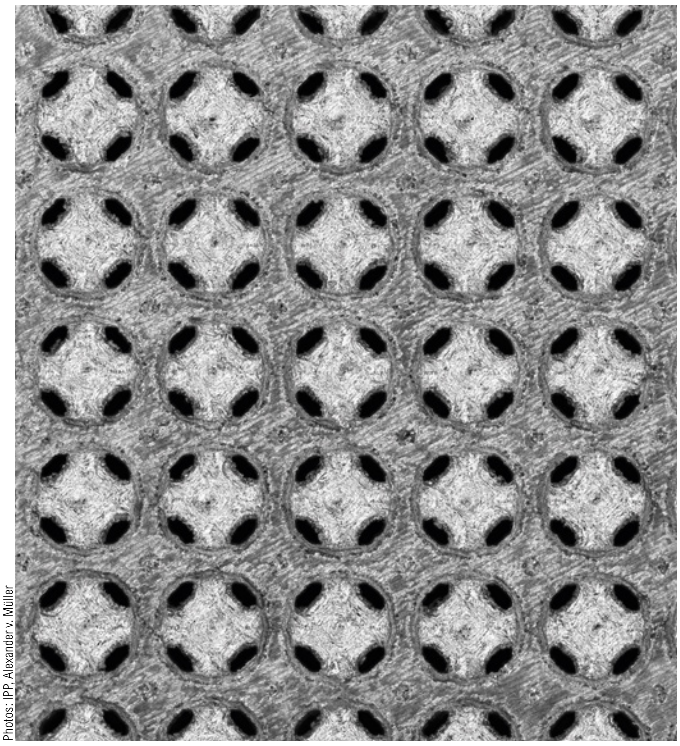
Mock-up of a plasma-facing component with a heat sink based on a copper-infiltrated tungsten honeycomb structure

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

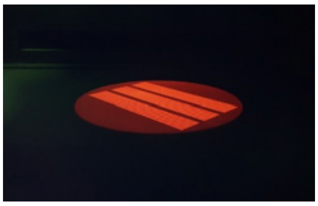


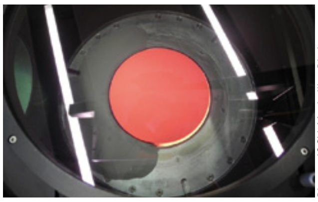
Photos: IPP, Alexander v. Müller

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.





Preheated tungsten build platform during the additive manufacturing process

Photos: IGCV, Maximilian Binder

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

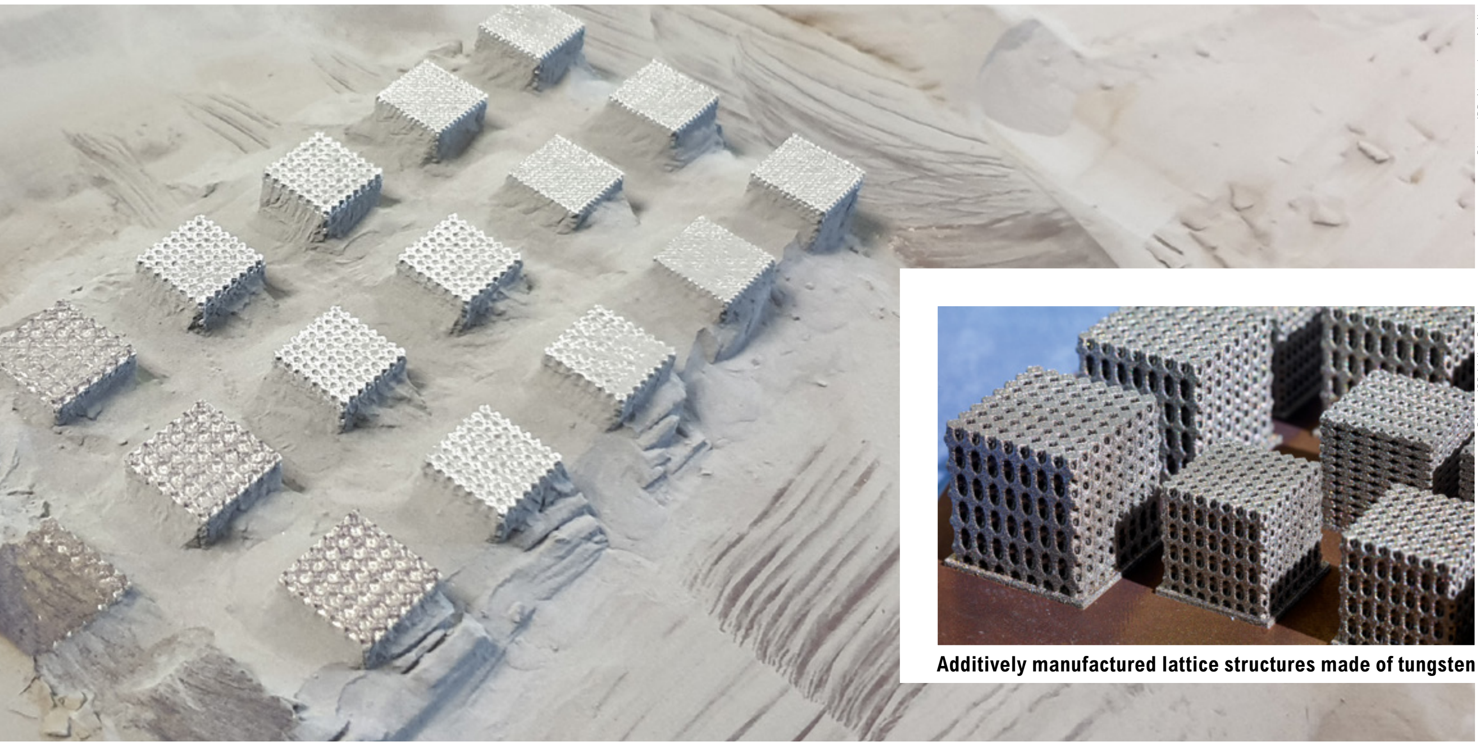


Photo: IPP, Alexander v. Müller

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

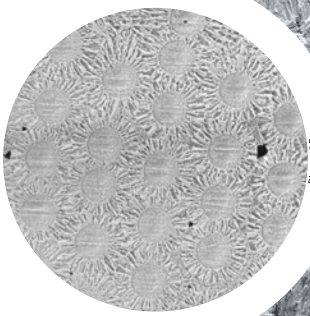


Photo: IPP

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.

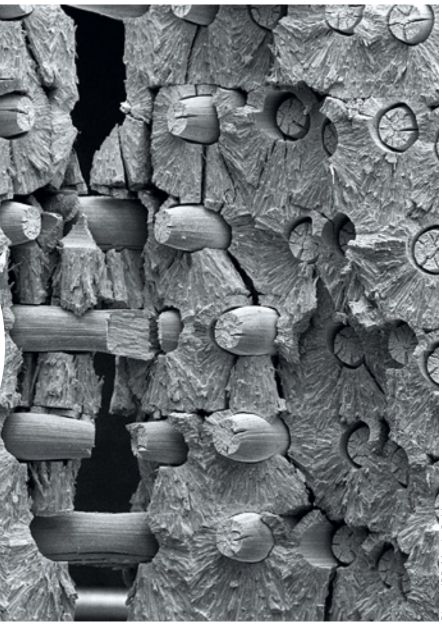


Photo: IPP, Martin Balden

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.

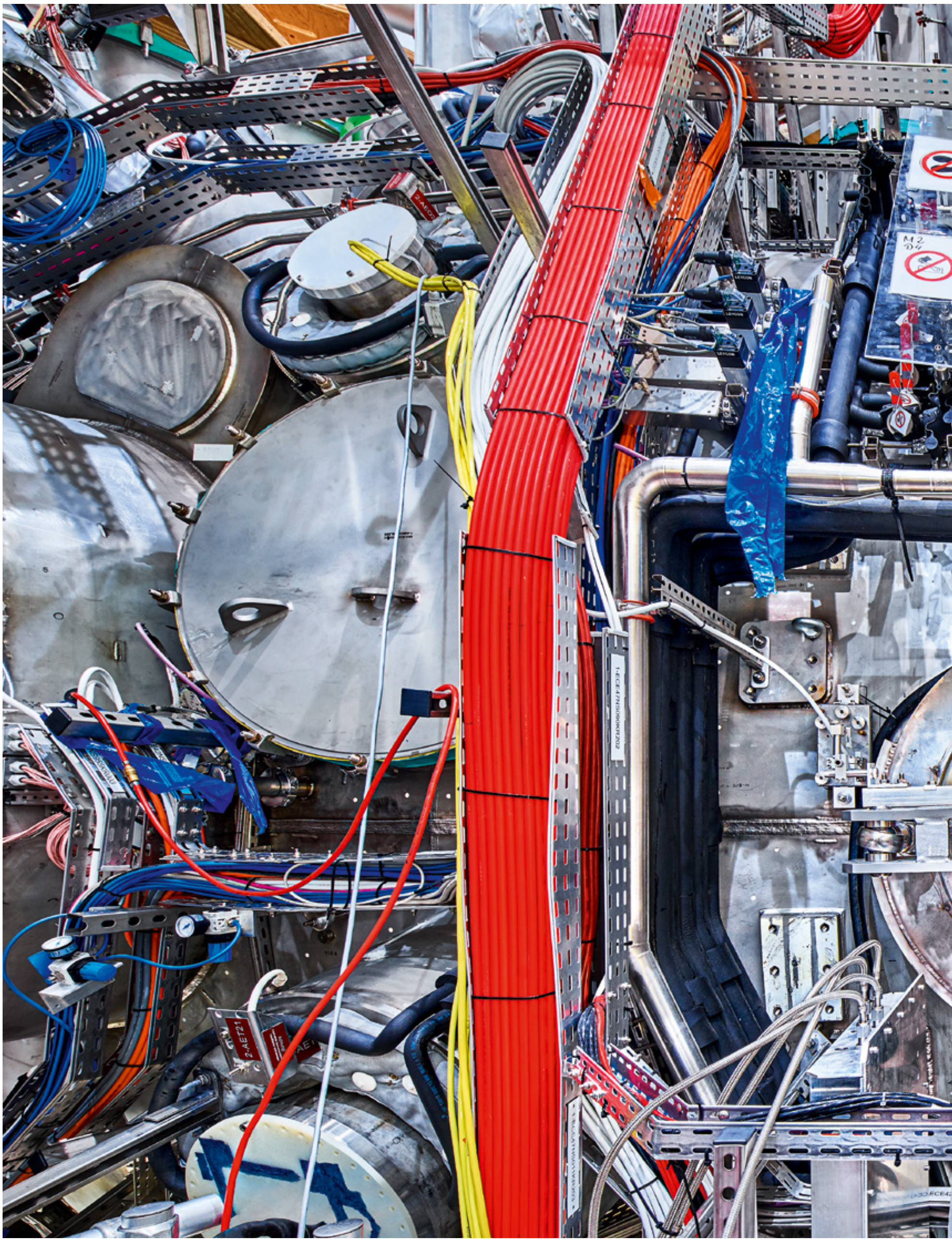
Imprint

Max Planck Institute for Plasma Physics
Boltzmannstraße 2 | 85748 Garching | Germany | Phone +49 89 3299-01

Greifswald Branch
Wendelsteinstraße 1 | 17491 Greifswald | Germany | Phone +49 3834 88-1000

www.ipp.mpg.de | info@ipp.mpg.de
IPP is also featured on Facebook, Twitter, Instagram, YouTube and LinkedIn.

2021, extended and revised edition | Photo title and back page: Luca Zanier



MAX PLANCK GESELLSCHAFT

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

EUROfusion