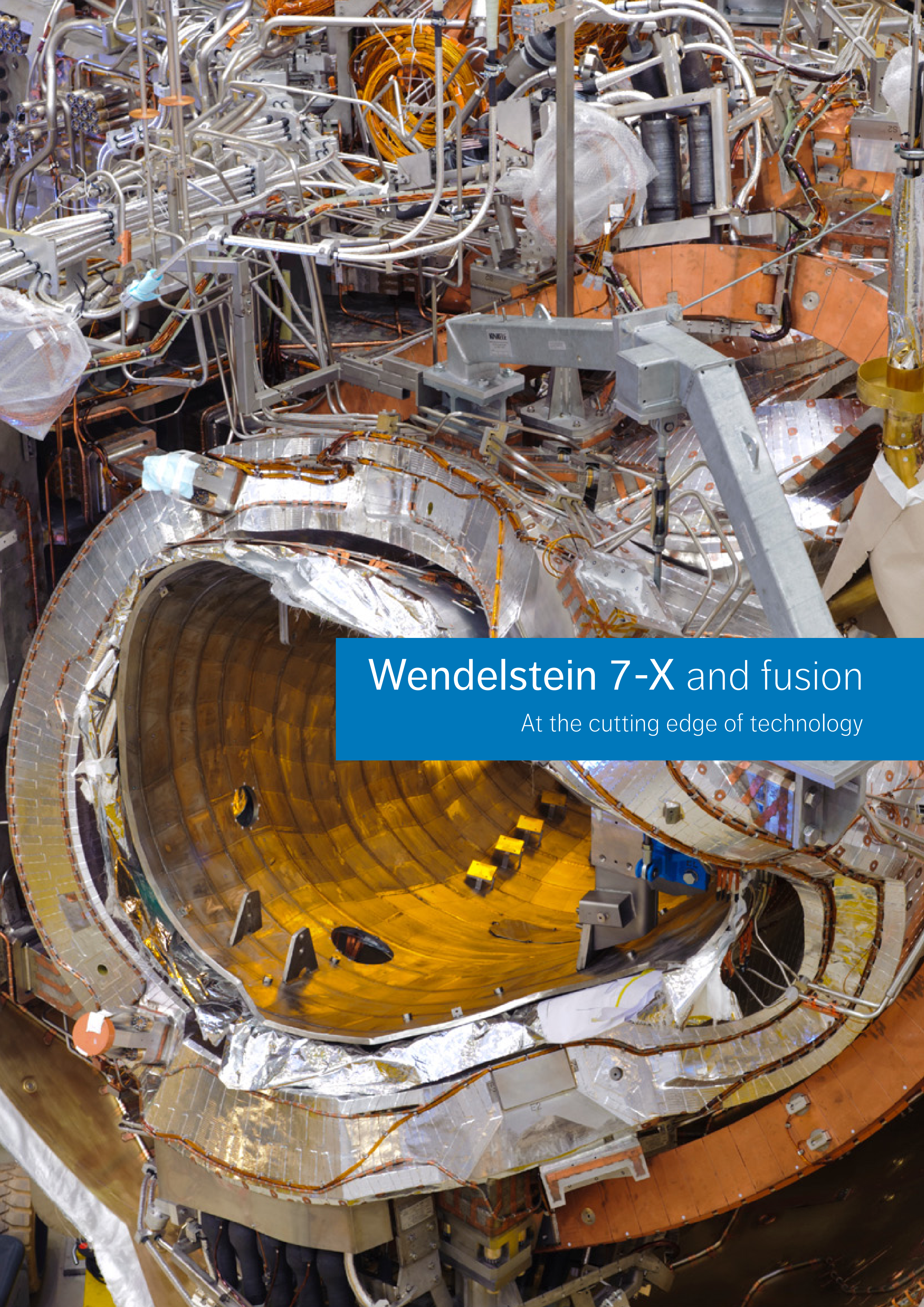
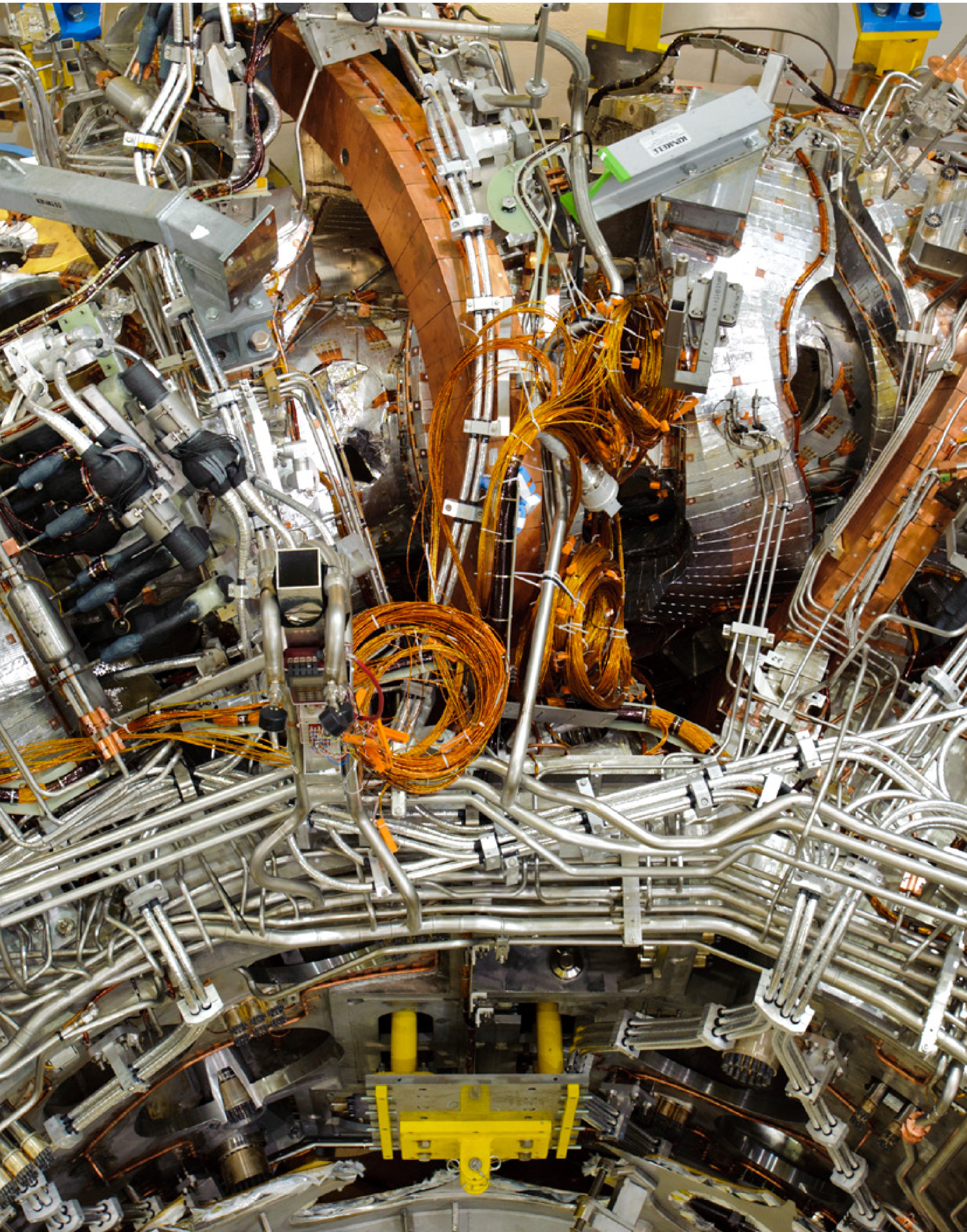
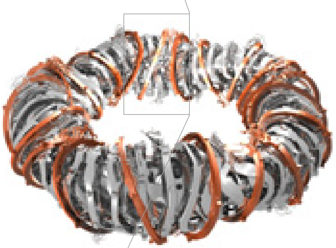
Wendelstein 7-X and fusion

At the cutting edge of technology





At the cutting edge of technology



How can industrial companies benefit from fusion research contracts?

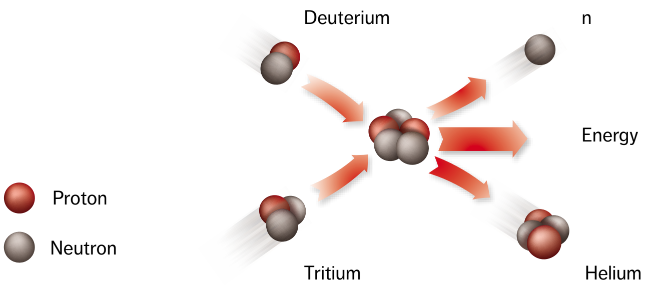
Securing reliable energy supplies will remain a major challenge in this century. Currently, fossil fuel resources (oil, natural gas and coal) meet about 90 percent of the worldwide energy demand. These energy resources are not only being rapidly depleted, but also cause damage to the environment due to carbon dioxide emissions.
By 2100, the global demand for electricity will probably have increased dramatically by a factor of six. Thus, in the long term, it is inevitable that the energy supply system will be restructured.
Since the 1950's, scientists and engineers the world over have been investigating an alternative source of energy: nuclear fusion. Research has been directed towards the development of a power plant capable of generating energy from the fusion of light atomic nuclei. For this purpose, the fuel (a dilute, ionised hydrogen gas, or plasma) must be contained in a magnetic field. This plasma must be heated to an ignition temperature of more than 100 million degrees Celsius and the reaction maintained under stable conditions.
Developing a fusion power plant is a technological and scientific challenge that has almost reached the limits of what is achievable technically. In these developments industrial partners play a key role throughout, both in achieving new heights in technological excellence and in using the acquired know-how to expand their business into new areas. Fusion research institutions and their industrial partners therefore develop and implement together new, innovative solutions on a wide front.

By taking the industrial companies involved in the construction of the fusion experiment Wendelstein 7-X as examples, this brochure demonstrates that the partners of fusion benefit not only directly from the contracts awarded, but also, and sometimes primarily, from the increase in their expertise and from their improved market position.

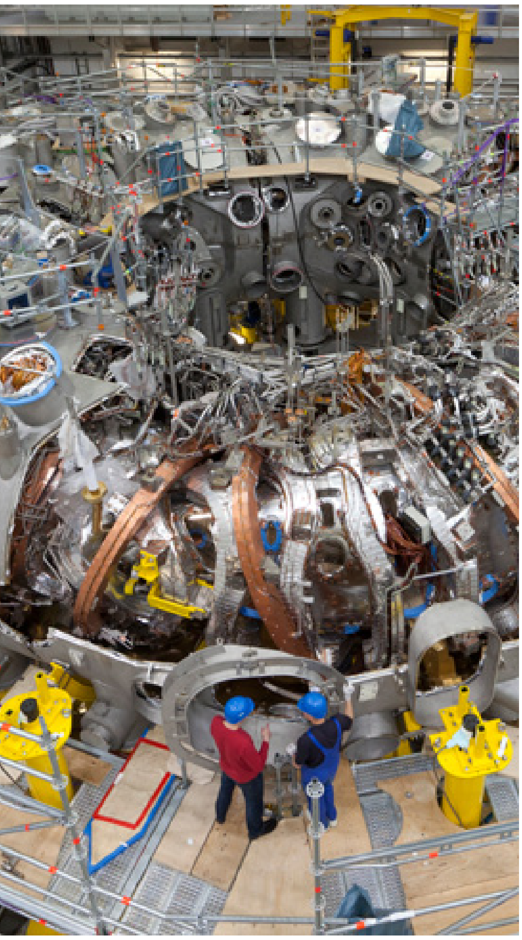
Wendelstein 7-X

The Max Planck Institute for Plasma Physics (IPP) conducts research into the theoretical and physical principles underlying fusion power plants. Worldwide, it is the only institute that investigates both important types of fusion device: the tokamak and the stellarator. The ASDEX Upgrade tokamak is in operation in Garching and the Wendelstein 7-X stellarator is under construction in Greifswald.

Nuclear fusion reaction scheme

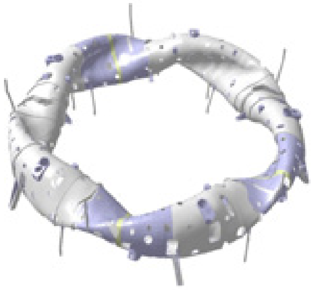


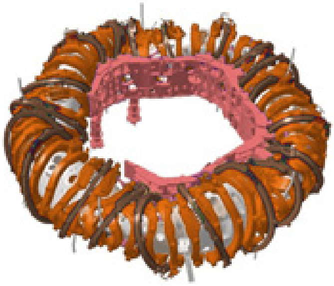
Hydrogen nuclei fuse in the sun and stars under enormous gravitational pressure. A fusion power plant on Earth, however, must operate on another principle. Under terrestrial conditions it is the two types of hydrogen, deuterium and tritium, which react most easily. They form a helium nucleus; a neutron 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 11 tons of coal.

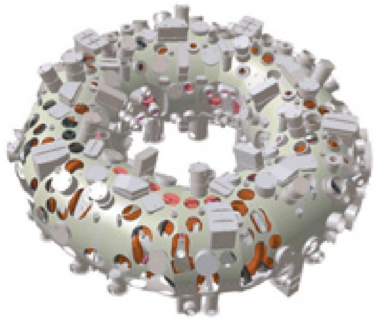


The optimized Wendelstein 7-X device will demonstrate the suitability of the stellarator device as a power plant. Discharges of up to 30 minutes will demonstrate its essential property, namely, that of continuous operation.
A key part of the experiment is the coil system, which consists of 50 non-planar 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 will flow 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 10 megawatts, radio wave heating with 4 megawatts and neutral beam injection heating with 20 megawatts.
Companies from all over Europe have worked closely with the Max Planck Institute for Plasma Physics in developing and manufacturing the Wendelstein 7-X 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.

The five Wendelstein 7-X modules rest on the foundation of the machine.





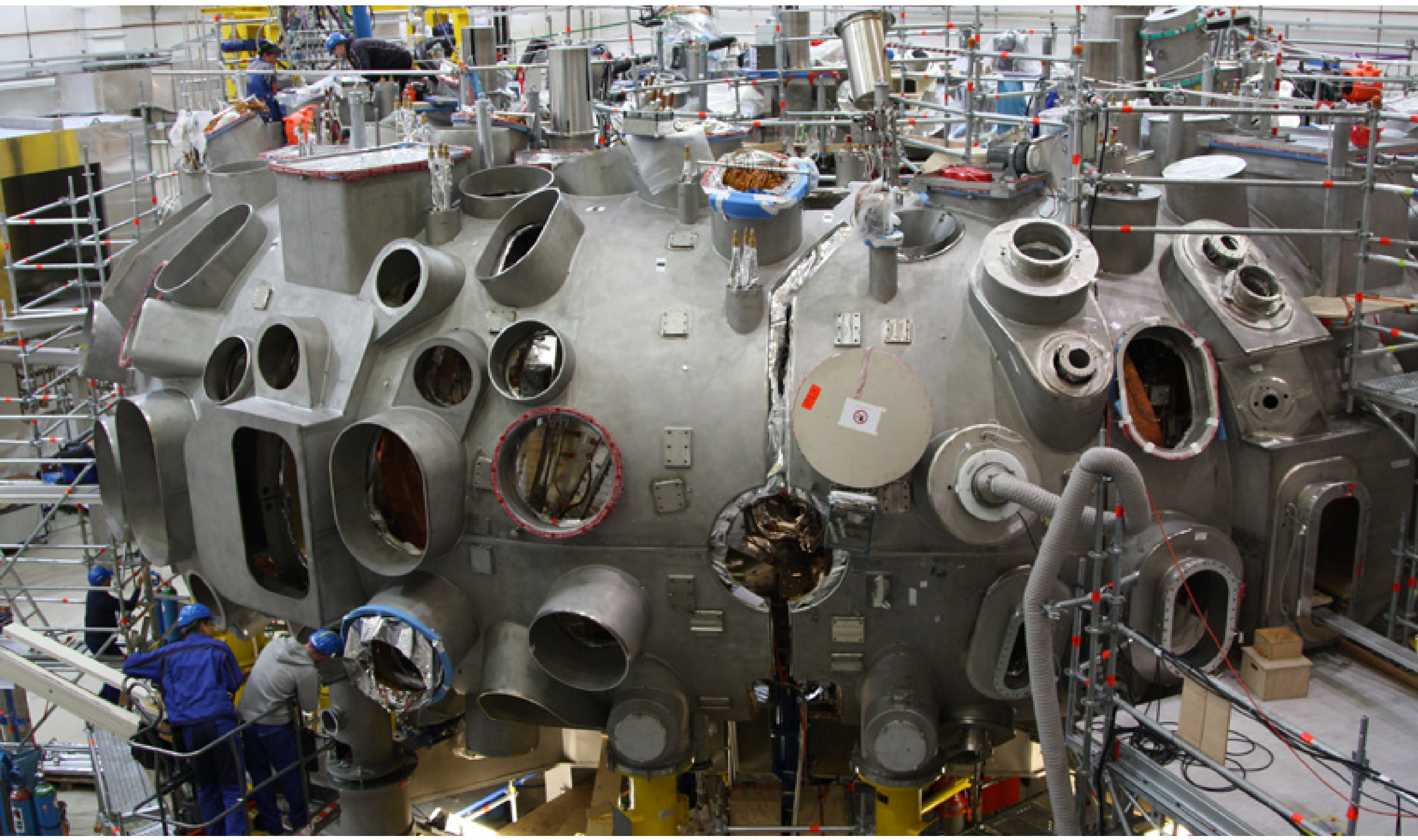


Graphic depictions of Wendelstein 7-X: plasma vessel, coil support structure with central ring, outer vessel

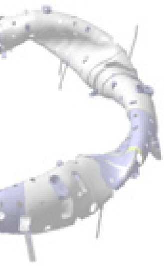
Five almost identically built modules constitute the Wendelstein 7-X device. Each module consists of a part of the plasma vessel, its thermal insulation, ten superconducting stellerator coils, and four interconnected planar coils, as well as the pipe system for cooling the coils, a segment of the supporting central ring and the outer vessel.

All five modules have now been positioned on the foundation of the machine. Considerable work remains to be done until the device goes into operation in the summer of 2014: The modules need to be welded together; the connections for heating and monitoring the plasma and the lining of the plasma vessel must be mounted. Simultaneously, the heating systems and the cooling system that will supply the coils with liquid helium must be constructed and then connected to the machine. Furthermore, various measuring instruments are being developed and manufactured and must be installed.

The five modules rest on the foundation of the machine and must be connected together



Large corporations



MAN Diesel & Turbo SE, located in Deggendorf, Germany

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

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 at roughly 100 million degrees. The almost ring-shaped plasma chamber has an outer diameter of 12.8 metres and a height of 2.5 metres. The steel vessel must match precisely the symmetry of the magnetic field which confines the hot plasma. The requirements placed on the steel vessel constructed by MAN Diesel & Turbo thus presented completely new and challenging problems for the company: It was necessary to manufacture an unusually complex, three-dimensional vessel made of stainless steel of volume of 30 cubic metres with a dimensional tolerance of +/- 2 millimetres. The plasma chamber consists of altogether 200 rings. Each ring is composed of several 15 centimetre-wide steel strips, which are bent in order to achieve the required curved geometries. 20 sectors were then fabricated from the rings using welding techniques suitable for ultrahigh vacuum. The sectors were delivered to Greifswald where they were welded together onsite, resulting in the complete ring. The plasma vessel wall has roughly 300 ports of different size, which are necessary for heating the plasma and investigating it scientifically. MAN Diesel & Turbo in Deggendorf was a reliable partner in fulfilling its contractual obligations.

To successfully complete the project, the Deggendorf factory had to introduce and develop a variety of new technologies.

- Before manufacturing such a complex vessel, detailed computer models had to be developed. This prompted MAN Diesel & Turbo to introduce the most advanced program currently 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 Deggendorf MAN Diesel & Turbo applied an electronic, laser-assisted surveying system for the first time, which is now routinely used in all production at the company.
- Manufacturing the steel vessel was the greatest challenge for MAN Diesel & Turbo. The technology used, in particular the assembly of the vessel using single steel strips derived from pre-shaped segments, is extremely innovative but requires highly sophisticated welding techniques in order to prevent the welds from distorting. These technologies were put to the test in a spectacular way.
- Very precisely positioned steel brackets are required for the installation of the wall elements inside the plasma chamber. To achieve the accuracy required in a spatially confined environment, MAN Diesel & Turbo developed a six-axis robotic manipulator that is now used in the company for various routine applications. Furthermore, the company used three-dimensional water jet cutting technology to manufacture precisely the 300 openings for the ports.

Welding the Wendelstein 7-X plasma vessel

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

As a company, MAN Diesel & Turbo has benefited both directly and indirectly from these developments in steel construction. New technologies could be introduced, which were then improved together with the customer, the Max Planck Institute for Plasma Physics. MAN Diesel & Turbo has already applied these new procedures to manufacture chemical reactors. The engineers and technicians – already highly qualified - were able to increase their expertise and promote the competitiveness of the company.

Liquid helium cools the 70 magnetic coils of the Wendelstein 7-X device to -270 degrees, in order to make them superconducting. Once they have reached this state, the coils require almost no power. The plasma vessel, the outer vessel, and the 254 connecting pipes, which facilitate access to the plasma vessel, are shielded by the so-called thermal insulation. This consists of a wrinkled, multi-layer plastic foil coated with aluminium, which is in contact with an actively cooled shell. The engineers of MAN Diesel & Turbo in Deggendorf and the engineers and physicists of the Max Planck Institute for Plasma Physics successfully mastered this completely new and extremely complicated engineering problem. Thanks to their close collaboration, they have always found new solutions to the many engineering problems, and in the end produced optimal results.

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

Here are a few significant features:

- For the thermal insulation for the plasma vessel, actively cooled elements, which are called “shields” had to be manufactured. Due to the unconventional shape of the plasma vessel and the extremely confined 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. The solution was then found to be a shield made of fibreglass-reinforced plastic.
- Not only did the plastic shields have to be formed exactly to the unusual shape of 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 Diesel & Turbo Deggendorf meant that the company was taking a risk. Unlike the situation at normal construction sites, W 7-X represents a complex scientific environment, where the contractor has to react quickly to adjustments and changed requirements. This is typical for a “first of its kind” facility.

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

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

Facts:

Research institute:
Max Planck Institute for Plasma Physics
Industrial Partner:
MAN Diesel & Turbo SE
(Deggendorf, Germany)
Contracts:
Plasma vessel, cryostat, thermal insulation, wall panels and assembly

The manufacturing contract for the thermal insulation caused MAN Diesel & Turbo Deggendorf 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 unknown territory. In addition to fusion devices, cryogenic technology will be applied in the high-energy accelerators such as the TESLA project currently under construction in Hamburg and the FAIR project in Darmstadt.

Thales Electron Devices, Paris-Velizy, France
Element Six, Great Britain
Diamond Materials GmbH, Reuter Technologie GmbH, Germany

Heating plasma for Wendelstein 7-X
"A diamond window to the plasma"

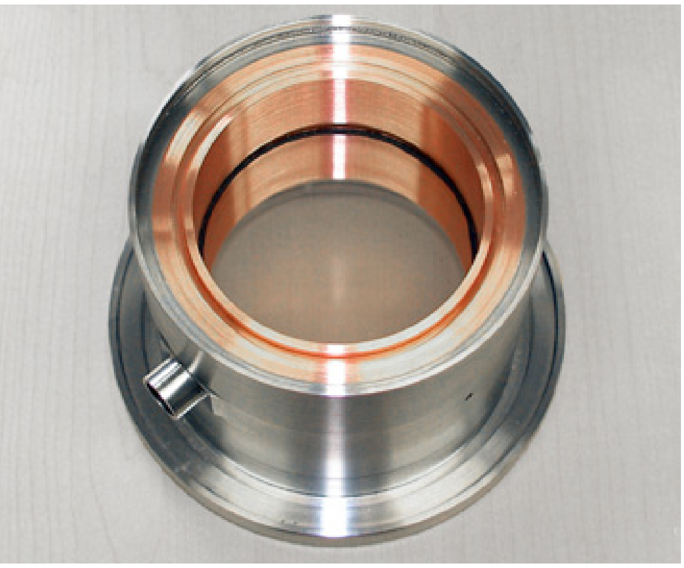
Ignition of a fusion reaction requires a heating system suitable for heating the plasma to 100 million degrees Celsius. Heating with microwaves has been considered a very interesting option. However, this technology requires the development and production of highly efficient microwave tubes capable of generating 1 million watts. The initial results were achieved in Russia, the United States and Japan a few years ago, 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 the Max Planck Institute for Plasma Physics.

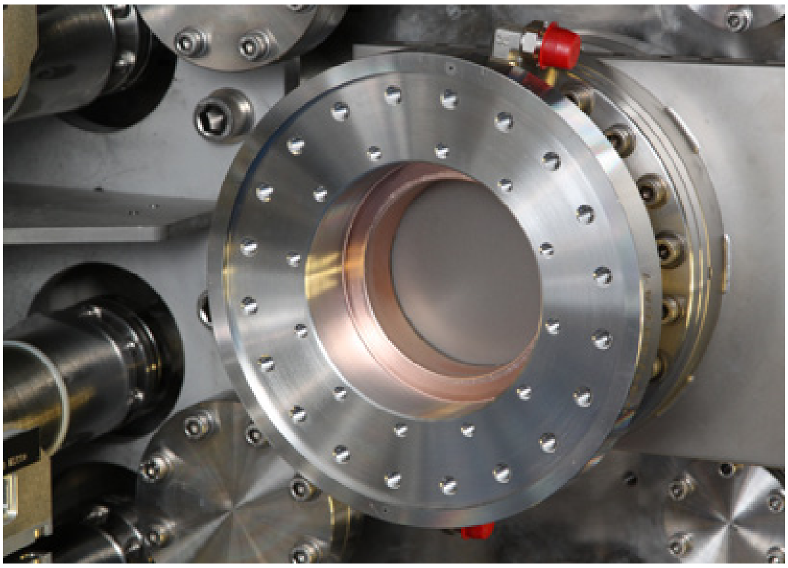
- The joint development of the prototype was so successful that the batch production could be started without delay. However, the consortium was then faced with new problems that arose during manufacturing, thus creating new technical challenges. During batch production, the ceramic material used had 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. Meanwhile, this solution has also been proposed for tubes built by Communication & Power Industries (CPI) in the United States.
- 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. TED successfully implemented this concept and made the breakthrough that improved the reliability of microwave tubes 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.
- 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 a possible. These diamond windows, which have been manufactured by Diamond Materials in Freiburg and Element Six in England, 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.

Thales SA: high-performance microwave tube for continuous operation

Thales SA: new beam tunnel for the microwave tube

- 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.





Reuter Technologie: Soldered diamond window using the CVD process in a diamond window

All these improvemements 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". TED, 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.

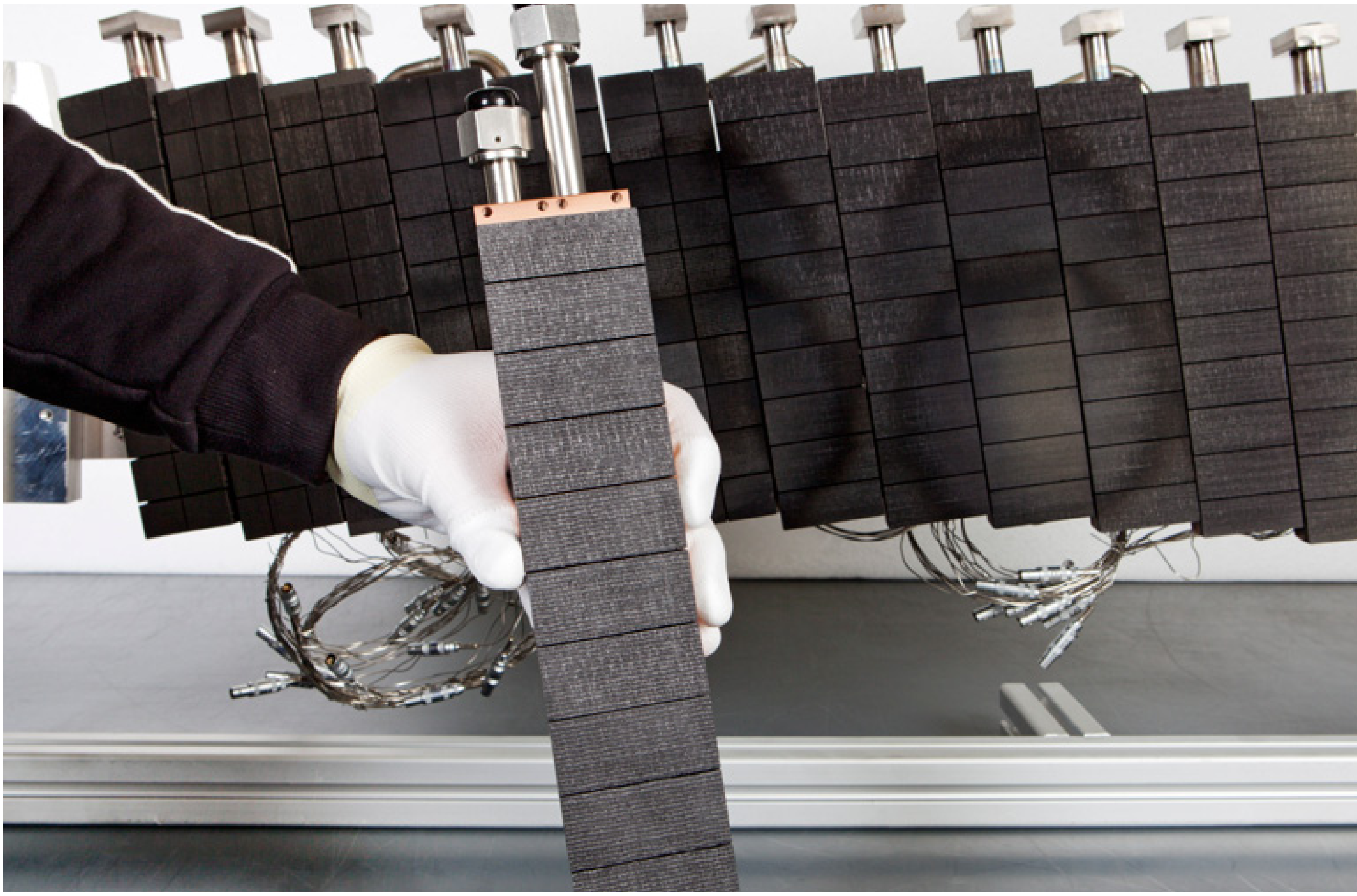
Facts:

Research institutes:
Karlsruhe Institute for Technology, Max Planck Institute for Plasma Physics, Stuttgart University
Industrial partners:
Thales Electron Devices, Microwave Tube Division (Paris-Velizy, France), Diamond Materials (Freiburg, Germany), Element Six (Ascot, London, Great Britain), Reuter Technologie (Alzenau/Schöllkrippen, Germany)
Contracts: Eight high-performance gyrotrons, each outputting 1 megawatts for 30 minutes

The high load Wendelstein 7-X wall „10,000 hotplates on one square metre"

Plansee SE, Reutte, Austria

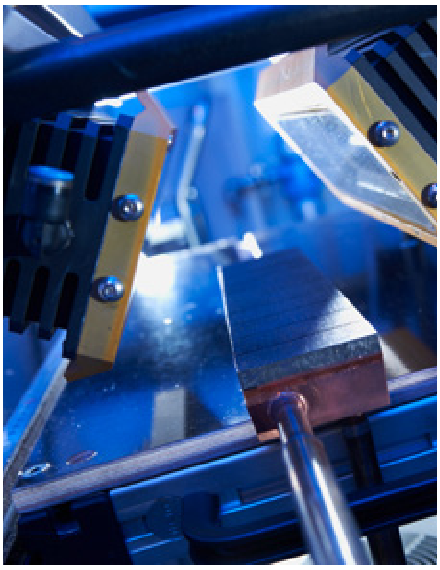
Heating fusion plasmas to temperatures of roughly 100 million degrees Celsius requires very high power outputs in the range of 10 million watts. Although the heated plasma inside the vessel will be confined by the magnetic field, contact between the plasma boundary and the wall segments cannot be avoided. The temperature of the plasma decreases dramatically from its centre to its outer boundary where it is "only" about 100,000 degrees Celsius. To protect the wall of the plasma vessel from damage, the



High-performance, water-cooled wall elements

huge heat flow from the plasma has to be conducted through the wall. The sections of the wall will be protected by water cooled wall elements made of carbon or metal. The high-performance heat exchangers are known as "divertors". Using the Wendelstein 7-X experiment the suitability of stellarators for continuous operation will be tested.

Large corporations



Target elements during thermographic testing

Thus, the development of high-performance divertors has become necessary. Plansee SE has designed so called "target elements" for the divertors, which must be continuously capable of withstanding 10 megawatts per square metre. A sophisticated combination of carbon-fibre-reinforced carbon and water-cooled metal blocks, also known as heat sinks, had to be been developed. Significant steps in this development were made in close collaboration with the Max Planck Institute for Plasma Physics.

- Joining the carbon-fibre-reinforced carbon to the water-cooled heat sink made of a metal alloy has 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 has 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. The Max Planck Institute for Plasma Physics, 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 10 million Watt per square metre mentioned above are higher than that placed on the edges of the wing of the space shuttle when it re-enters the atmosphere (6 million watts per square metre), which, however, "only" occurs for several hundred seconds in that case. Carbon-fibre-reinforced carbon tiles are also used in that application. Space technology and fusion technology have 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 (http://www. Extremat org.) has been carried out. Plansee played a leading role among the 30 project partners, which are predominantly from the industrial sector.

Facts:

Research institutes:
Max Planck Institute for Plasma Physics
Industrial partner:
Plansee SE (Reutte, Austria)
Contracts:
Development and production of elements for the first wall, particularly within the field of divertors

Using a technology that was introduced for the French fusion experiment, Tore Supra, Plansee and the Max Planck Institute for Plasma Physics have 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.

Ductile tungsten
“Creative structural materials for high temperatures”

Plansee SE, Reutte, Austria

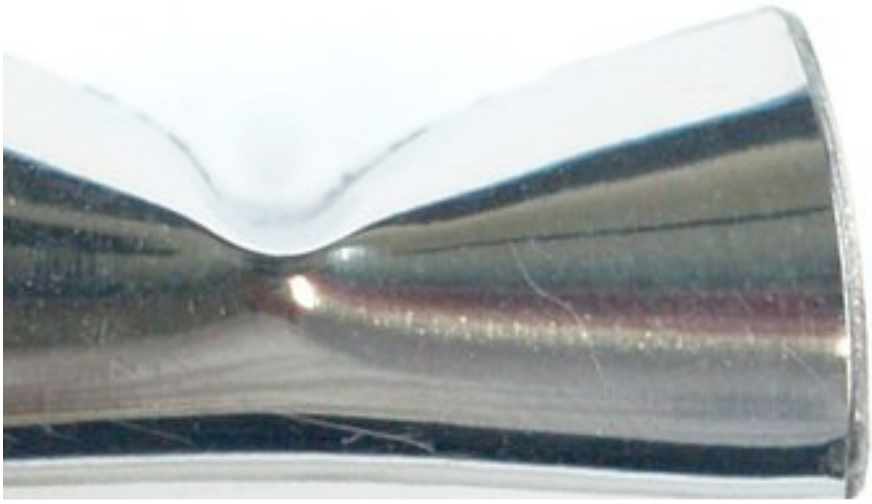
Components for fusion must offer high stability under extreme conditions. In particular, the divertor, which takes up the “helium ash” from the “burning” plasma is exposed to heat fluxes of 10 megawatts/m² or more.
Even those structural components protected behind a heat shield (such as the cooling channels) may reach operating temperatures exceeding 700 °C, and therefore need to have a high resistance to temperature and pressure, and, at the same time, some degree of plastic deformability.

Conventional pipes made of heat-resistant materials, such as tungsten, are not suitable structural materials due to their brittleness.
A completely new heat-resistant material based on tungsten foil has been developed in collaboration with Plansee. This laminate made of tungsten foil and alternating layers of “soft materials” consists of multiple bonded layers. It can be easily formed into a pipe as a result of its plastic deformability. Even at high pressures (up to 1,000 bar) and ambient temperatures, the test components did not exhibit fractures and remained intact.
The development of deformable tungsten is a promising approach not just for fusion research, but also for many other fields of application.

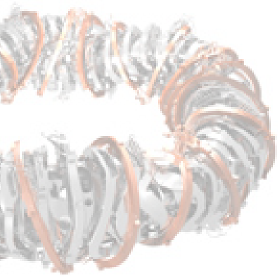
Plansee, together with the Karlsruhe Institute for Technology, has applied for a patent and hopes to be able to solve future materials problems at high temperatures as the provider of high-technology materials.

Facts:

Research institute:
Karlsruhe Institute for Technology
Industrial partner:
Plansee SE (Reutte, Austria)



Fractures in brittle, solid tungsten and the ductile behaviour of laminated tungsten notched-bar impact testing



Babcock Noell GmbH, Würzburg, Germany

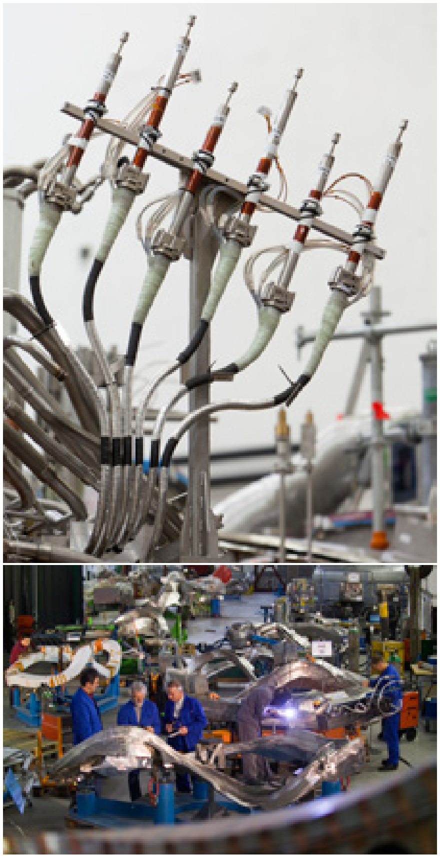
The plasma must be held at a temperature of 100 million degrees. Ring-shaped, twisted magnetic fields confine the plasma and thermally isolate it from the cold vessel walls. The true art now lies in finding the “correct” magnetic field. In stellarator-type fusion devices like Wendelstein 7-X, the magnetic field is determined exclusively by the geometry

Preparation of a non-planar coil for assembling

The superconducting magnetic coils for Wendelstein 7-X “Nature determined the form for us”

of the outer magnetic coils. The complex geometry of the Wendelstein 7-X coils is the result of ten years of systematic calculations using the supercomputers available in the late 80’s and 90’s. Because the shape of the coils is determined by the physics and calculated using strict optimisation procedures, they can be regarded as ideal. The technical realisation of the coil geometry was extremely challenging for the contractor. A consortium of companies and a European network involving many sub-contractors for the manufacture of various coil elements had to be set up. Numerous engineering problems had to be solved:

- In order to manufacture the superconducting, spatially complex winding packages for the coils, the consortium partners Babcock Noell and Ansaldo Superconductors S.p.A had to develop a special engineering process that would bring the superconductor into the necessary shape. Suitable winding packages were built and successfully introduced. Moreover, Babcock Noell acquired valuable experience in the design of steel casings and their manufacture using optimised casting moulds, including the embedding of the winding packages in the steel casings and their high-precision mechanical machining.
- Because they have to withstand very high voltages in the event of an emergency shutdown, the coils must be extremely robust. Each coil had to undergo a variety of high-voltage tests at up to 13,000 volts. One particularly sensitive voltage test was conducted in a dilute gas atmosphere. Deficiencies in the coil insulation caused visible discharges, which could then be rapidly located and the corresponding repairs carried out. The test (called a “Paschen Test”) was developed together with Babcock Noell GmbH as part of the coil testing procedure in the factory. The extraordinarily strict tests set new standards for the quality assurance of superconducting magnets.



Manufacturing non-planar coils for Wendelstein 7-X

The team of Babcock Noell GmbH has demonstrated its remarkable expertise in the completion of the Wendelstein 7-X contract. The know-how has since been used successfully for other projects and for bidding for the manufacturing contract for the ITER poloidal field coils. W7-X served as an important reference. At the beginning of 2012, the GSI Hemholtz Centre for Heavy Ion Research awarded Babcock Noell GmbH a contract for the production and delivery of 113 superconducting magnets for the Facility for Antiproton and Ion Research (FAIR) device in Darmstadt. Ansaldo Superconductors has successfully used the experience they gained from the W7-X coils in a consortium that has submitted an application to manufacture the ITER toroidal field coils and will manufacture the European winding packages.

Facts:

Research institutes:
Max Planck Institute for Plasma Physics, CEA Commissariat d’ Energie Atomique (Saclay, France)

Industrial partners:
Babcock Noell GmbH (Würzburg, Germany)
Ansaldo Superconductors S.p.A. (Genoa, Italy)

Contracts:
Fifty superconducting non-planar coils

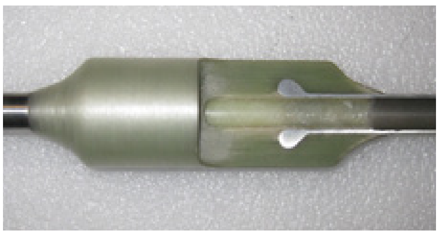
Babcock Noell GmbH, Würzburg, Germany

The superconducting magnets, which produce the necessary magnetic field for the plasma confinement in a fusion reactor, are cooled to cryogenic temperatures with liquid helium. The helium flows through metal pipes to the magnets, which are held at high voltage.

Axial High Voltage Divider
"Powerful discharges safely buffered"

In the case of an emergency shutdown, the magnets can generate voltages of up to more than 10,000 Volt. Therefore, a high-voltage divider must be installed between the metal feed lines and the pipe system.
The high-voltage divider must ensure that the helium lines inside the magnets are electrically insulated. It has to prevent leaks and arcs, which may occur in the event of discharges and arcs inside the magnet, and thus help to maintain the necessary helium cooling for the magnets.

Qualified 5 kV divider after successful high-voltage and material testing



Babcock Noell can now manufacture dividers for different temperature ranges in large-scale production. The efficiency of these dividers has been proven by the Karlsruhe Institute (KIT) with qualified high-voltage and materials tests. The prototypes withstood -196 °C, 70 kV and 60,000 cycles undamaged and were leak-free. They are thus qualified for ITER.

Babcock Noell can thus provide dividers which set new standards with regard to vacuum-tightness, mechanical robustness and high-voltage resistance.
These specifications will help to market the dividers not only in the field of fusion but also for the GSI/FAIR project.

Facts:

Research institutes:
Karlsruhe Institute for Technology
Industrial partner:
Babcock Noell GmbH (BNG)
(Würzburg, Germany)
Contracts:
Development of a high-voltage divider for ITER

Refrigeration system for Wendelstein 7-X "Close to absolute zero"

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

The Wendelstein 7-X magnets must be cooled to a temperature of −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. The helium has to be liquefied to the required temperature using a large refrigeration system. Since this involves a closed-loop cooling system, the system must be able to react with exceptional flexibility to the various operational states of the magnets. Linde AG has developed the industrially available technology significantly further. The flexibility required of the cryogenic system has been accomplished through the adroit combination of turbines, cooling compressors and cold circulators. A storage tank for the liquid helium makes rapid increases in performance possible. Overall, the helium refrigeration system at Wendelstein 7-X is one of the most modern and flexible systems worldwide.

Linde Kryotechnik was able to develop its expertise in the design and construction of complex large-scale refrigeration systems through the construction of the highly specialised, highly flexible Wendelstein 7-X system and thus further qualify itself for new, major projects.

Facts:

Research institute:
Max Planck Institute for Plasma Physics
Industrial partners:
Linde AG (Munich, Germany) and
Linde Kryotechnik (Pfungen, Switzerland)
Contracts:
Helium liquefaction system

View into the Wendelstein 7-X refrigeration system

EADS-RST, Rostock, Germany

Assembly equipment, which allows alignment for all six degrees of freedom, is used for mounting the coils, ports and in-vessel components. Such equipment can only be operated in a restricted way due to the tight space requirements. Moreover, extremely precise specifications must be taken into consideration. EADS-RST manufactured two manipulators for the precision positioning and alignment of the coils (3.5 metres high and 6 tons in weight), an assembly system that can be rotated and positioned precisely, straddling the machine, and a manipulator that takes over the high-precision positioning of installed components in the restricted space of the plasma vessel using computer control systems.

Development of special mounting equipment “Six tons positioned with clockwork precision”

Facts:

Research institute:
Max Planck Institute for Plasma Physics
Industrial partner:
EADS-RST (Rostock, Germany)
Contracts:
Construction, manufacturing and set up of special equipment for mounting at Wendelstein 7-X

EADS-RST has developed a complex manipulation technology for the Max Planck Institute for Plasma Physics that makes the optimal use of the available space. These handling systems are practical, stable and achieve a precision of up to 0.5 millimetres. The contracts have furthered significantly the construction and manufacturing expertise of the company, and will allow it to become a provider of complex manipulation technology to a greater degree in future. EADS-RST has acquired detailed know-how on the positioning and controlling of various pieces of precision equipment, which can be used economically with sub-millimeter precision in the range from a few kilograms to several tons even where access and direct observation are restricted. These insights will extend the service potential of the company for the development of equipment for customised machine construction. In the meantime, the company has received requests from other German research institutions for the development of customised equipment and is planning to expand its cooperative efforts in future.

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

Small and medium-sized enterprises

Kraftanlagen Heidelberg GmbH, Germany

HELOKA-LP – testing device for components for fusion research
"Special fusion materials require special test equipment"

The Helium Loop Karlsruhe-Low Pressure system (HELOKA-LP) plays an important role in the development of the International Fusion Materials Irradiation Facility (IFMIF). IFMIF is a planned irradiation facility for research into, and the licensing of, new materials that will be used for near-plasma components in the first fusion power plant. These materials must be resistant to the very high temperatures and high-energy neutron flux, which are produced during the fusion process. In IFMIF the neutrons are produced with the help of a particle accelerator. In particular, new types of steel will be tested in optimised irradiation modules. Equipment that will be developed with HELOKA-LP will be used for measuring the flow of energy in the helium coolant.
Kraftanlagen Heidelberg GmbH, as general contractor, has solved a number of problems in the design and construction of the HELOKA-LP systems.

- The heating by neutrons naturally occurring in IFMIF will be simulated in the HELOKA-LP experiments with electrical heating. This system had to be designed and built.
- HELOKA-LP will supply the necessary gas flows. It will include a helium circulatory system and a compressed air line, powered by a helium compressor (350 kilowatts) and an air compressor (500 kilowatts). As a light, mobile gas, working with helium at the required pressures and temperatures is very demanding.
- In addition, a helium supply system, including a vacuum unit, has been supplied for the system, in order to guarantee the availability and purity of the helium gas. Purity is an important factor for counteracting corrosion problems.
- Using a complex control system a broad range of operating conditions (pressure, temperature and mass throughput) can be achieved at the entrance of the prototype irradiation module. The measurement of the cooling efficiency is a necessary part of the quantitative characterisation of the module. The set-up will be run by a process control system (Siemens PCS7) allowing fully automatic operation. All test parameters will be recorded and documented during operation by means of a fast data acquisition system (100 milliseconds) which will also assist the operator with the analysis of the test sequences.

Helium systems with comparable parameters have not yet been constructed. Thanks to the collaboration the Karlsruhe Institute for Technology, Kraftanlagen Heidelberg GmbH has been able to acquire new know-how, and is well positioned for participating in the future IFMIF cooling system and additional subsystems (for example, the remote handling facility).

The HELOKA test system at the Karlsruhe Institute for Technology

Facts:

Research institute:
Karlsruhe Institute for Technology
Industrial partner:
Kraftanlagen Heidelberg GmbH
(Heidelberg, Germany)
Contracts:
Complete design and construction of the
Helium Loop Karlsruhe (HELOKA-LP)

Thomson Broadcast, Turgi, Switzerland

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

Facts:

Research institute:
Max Planck Institute for Plasma Physics
Industrial partner:
Thomson Broadcast (Turgi, Switzerland)
Contract:
High-voltage DC power system

A 130 kilowatt high-voltage DC power supply, with a peak performance of 24 megawatts in continuous wave operation, has been developed for the various heating systems on Wendelstein 7-X. Above all, this power system must fulfil the high demands of the microwave tubes (see above). The normal systems available from 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 reducing the residual ripple.

Switching stage racks for the high-voltage DC power system

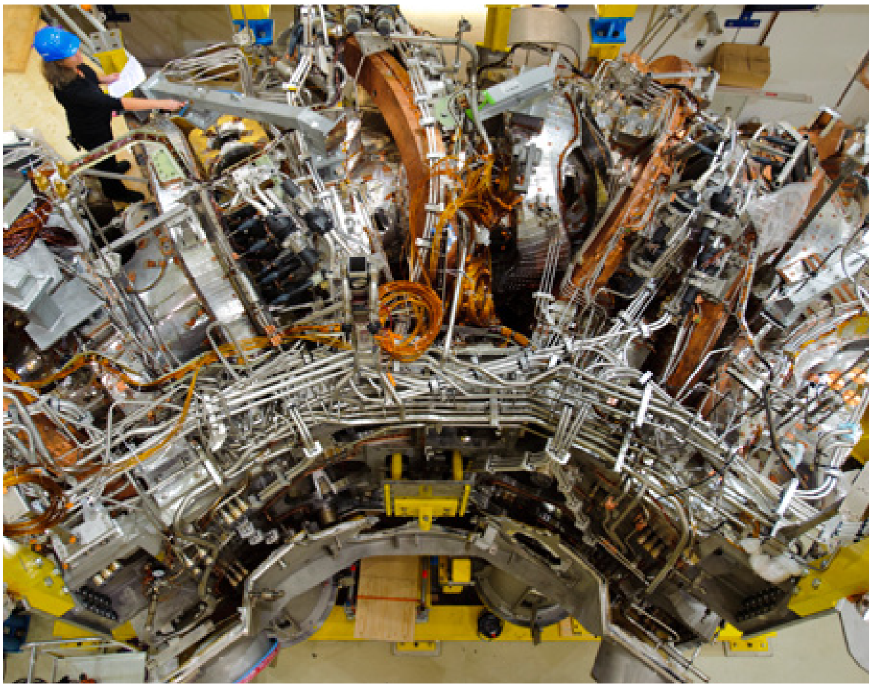
With the developments described above the Thomson Broadcast high-voltage power systems are now in a better position on the world market.

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

Dockweiler AG, Neustadt-Glewe, Germany

A total of four thousand five hundred metres of pipes for cooling water will have to be 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 the precisely aligned branching connectors would cost a great deal of time. Dockweiler found a solution. This company is capable of installing the extrusions or so-called “necks”, at an angle of up to 60 °C on the pipes. To accomplish this, a metal ball is drawn through a hole drilled in the stainless steel pipe, creating a neck. The connecting pipe can be connected to the finished neck by means of well-defined and highly precise orbital welding techniques.

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



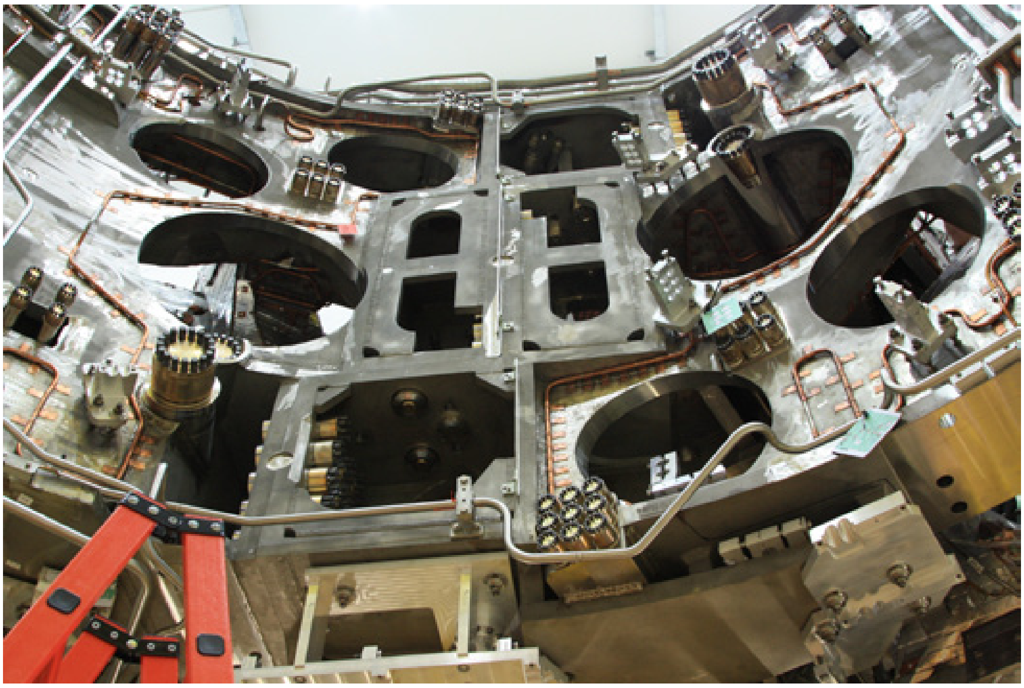
Dockweiler first began manufacturing three-dimensional pipe systems with the contract for Wendelstein 7-X. The company created their own measurement and bending techniques from scratch and acquired the corresponding machines, which will make the manufacturing of even more complicated pipe systems possible in future. As an additional requirement, Dockweiler had to first master the special quality requirements of ultra-high vacuum technology. The knowledge acquired during this process will provide the company access to new fields of business.

Facts:

Research institute:
Max Planck Institute for Plasma Physics
Industrial partner:
Dockweiler AG (Neustadt-Glewe, Germany)
Contracts:
Coolant pipe systems for the plasma vessel and the cryostat

CLP, Borgo San Dalmazzo, Italien

Assembling the central ring – "micrometre precision work"



Wendelstein 7-X central ring

The superconducting magnetic coils for Wendelstein 7-X are bolted to a massive central ring. This steel ring will be subject to forces of roughly 100 tons. For that reason, the ten individual ring segments have to be positioned with high precision. These steel segments weighing several tons and standing several metres 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 metre) 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. To check the precision, computer-controlled measurement procedures were designed together with CLP and successfully implemented. Special deep drilling techniques were developed for connecting the segments to each other using long screws made of special steel.

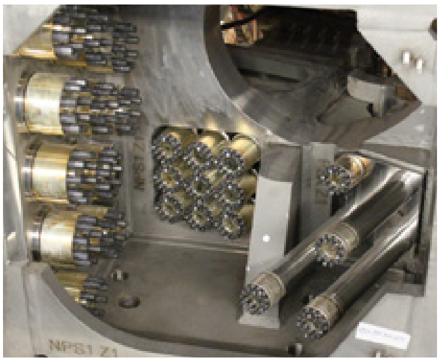
Working on the central Wendelstein 7-X ring has opened completely new areas of work for the company, as well as additional fields for contracts. In accomplishing this, the company now belongs to the companies qualified for ITER and has already received an ITER contract.

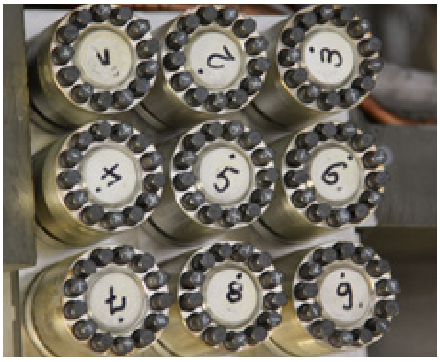
Facts:

Research institute:
Max Planck Institute for Plasma Physics
Industrial partner:
CLP (Borgo San Dalmazzo, Italy)
Contracts:
Mechanical assembly of the central ring module

Nordlock AG, Standort St. Gallenkappel, Switzerland

The ten individual segments of the central ring described above had to be bolted to each other. The 70 superconducting coils have also been fastened to the ring using bolt connections. These guarantee a certain degree of flexibility in comparison with welding. During the operation of Wendelstein 7-X, they will have to bear the heavy loads created by the magnetic forces, on the one hand, and by the extremely low temperature of -270 degrees Celsius, on the other. Nordlock AG provides bolts made of high-strength Inconel 718 with threads between M20 and M90 and lengths between 100 and 1350 millimetres. However, the friction co-efficient did not meet the requirements for the assembly of the components. The higher the friction co-efficient is, the greater the force has to be holding the bolts in place. For that reason, the company 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 friction co-efficient to 0.06. Previously, this co-efficient was in the range of 0.12 to 0.14 using special lubricants. Moreover, the exceptionally low friction co-efficient will remain constant over multiple clamping procedures, which avoids the need to re-lubricate hundreds of bolts during possible re-assembly work. The low friction co-efficient also allows the use of smaller torque wrenches, which simplifies assembly in the very restricted construction space at Wendelstein 7-X.



Ongoing development of bolt connections "Bolted, not welded"

High levels of tension can be achieved quickly thanks to the ongoing development of the SUPERBOLT system and a new procedure for tightening the nuts. This now belongs to the standard procedures at Nordlock AG.

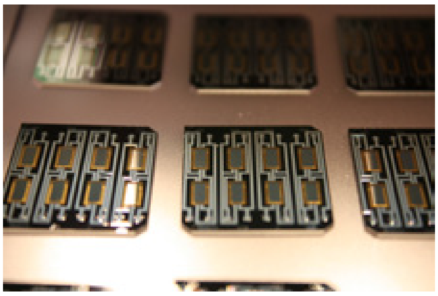
Facts:

Research institute:
Max Planck Institute for Plasma Physics
Industrial partner:
Nordlock AG (formerly P&S Vorspannsysteme AG), (St. Gallenkappel, Switzerland)
Contracts:
Further development of the SUPERBOLT system

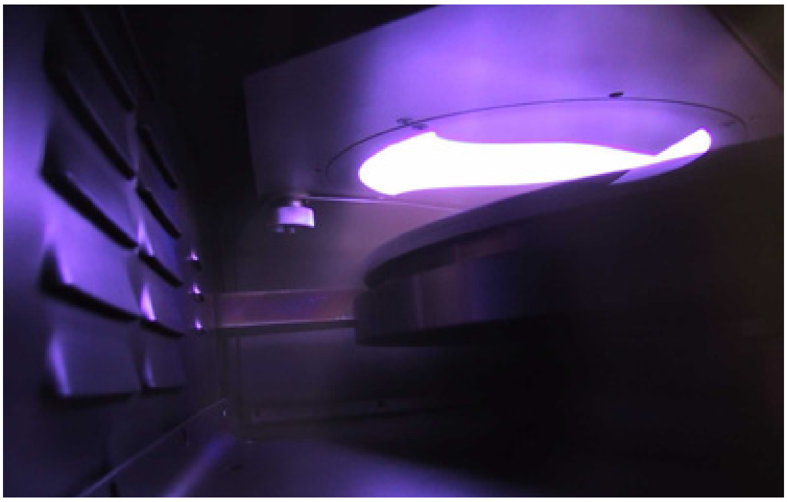
Institut für Mikrotechnik Mainz GmbH, Germany

Development of an ideal bolometer detector "Thickly coated platinum"

The demanding conditions for the diagnostic techniques on the ITER fusion experiment present significant challenges for the development of bolometer diagnostics. The detector not only has to be operated at temperatures higher than those used in previous fusion experiments, but will also be exposed to significantly higher neutron fluxes. For those reasons, new materials needed to be found for the detector. Due to the low capture cross-section for neutrons, platinum mounted on a membrane of silicon nitride was chosen as the material for the absorbing and conducting circuits. The Institut für Mikrotechnik Mainz GmbH (IMM) made available its skills in the field of thin coating techniques and the required infrastructure. Until now, all of the necessary processing steps have been developed as part of a development contract scheduled for three-and-a-half years for the delivery of a twelve-micrometer thick platinum absorber with a surface area of six square millimetres galvanised to a silicon-nitride membrane at a three micrometer thickness and twelve-and-a-half square millimetres in a pit etched from a silicon wafer. Together with IPP, the prototypes are now being tested in cooperation with the Max Planck Institute for Plasma Physics in Garching and further optimised, so that their parameters will be ideally adapted to the ITER requirements..



Optimised bolometer detector using a platinum absorber for delivery



Plasma lamps during sputter coating

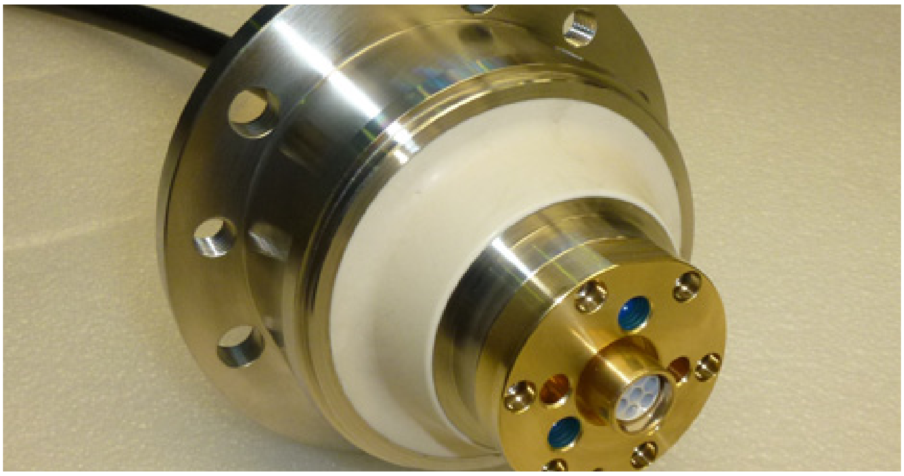
Facts:

Research institute:
Max Planck Institute for Plasma Physics
Industrial partner:
Institut für Mikrotechnik Mainz GmbH (Mainz, Germany)
Contracts:
Development of an optimised bolometer detector for use in the ITER project

Normally, the platinum galvanising technique is used by the jewellery industry, but only for coatings of roughly one micrometer thick. IMM has developed processing steps for manufacturing bolometer detectors, which lead to platinum layers thicker than 10 micrometers for the first time, thus giving them their unique characteristics. Furthermore, individual processes have been developed for adding and removing the platinum coatings in the appropriate galvanic solutions, so that IMM could acquire additional skills in this field.

The ITER cable feedthrough
"The reply from the vacuum – high tension and safe"

ODU Steckverbindungssysteme GmbH & Co.KG, Mühldorf/Inn, Germany



The plug of the vacuum-tight bushing with special insulation (white/blue) for high-voltage applications

The operation and control of a device requires measuring the signals from the necessary components. The transmission of signals from the source to the control point is – depending on the specified purpose – a complex challenge and requires appropriate functional solutions.

On the international Tokamak experiment ITER these signals can have voltages of more than 10,000 V. They must be transmitted out of the cryostat vacuum to the control room. In order to avoid costly interruptions of operation, it must be ensured that the vacuum of the cryostat is maintained and voltage spikes, which might occur as a result of an emergency shut-down of the magnets, can be absorbed without the risk of discharges or arcing. Such cable feedthroughs, or bushings, are currently not available commercially.

Fusion reactors are complex and require very many cable bushings. Together with the company ODU that specialises in manufacturing connectors, a design suitable for industrial large-scale production has been developed and implemented. The high-voltage cable bushing, consisting of a vacuum-tight socket connected to the cryostat and the corresponding plug is made up of a special multi-layer high-voltage resistant insulation made of glass-fibre reinforced plastic, in which the various signal lines are embedded.

The extreme requirements put on these cable bushings needed an effective combination of scientific know-how and product engineering. The prototype has since been tested successfully.

The company ODU is now qualified for the manufacturing of vacuum tight bushings suitable for several 10 000 V. In future, this know-how can also be used for the optimization of connectors used in many other fields.

Facts:

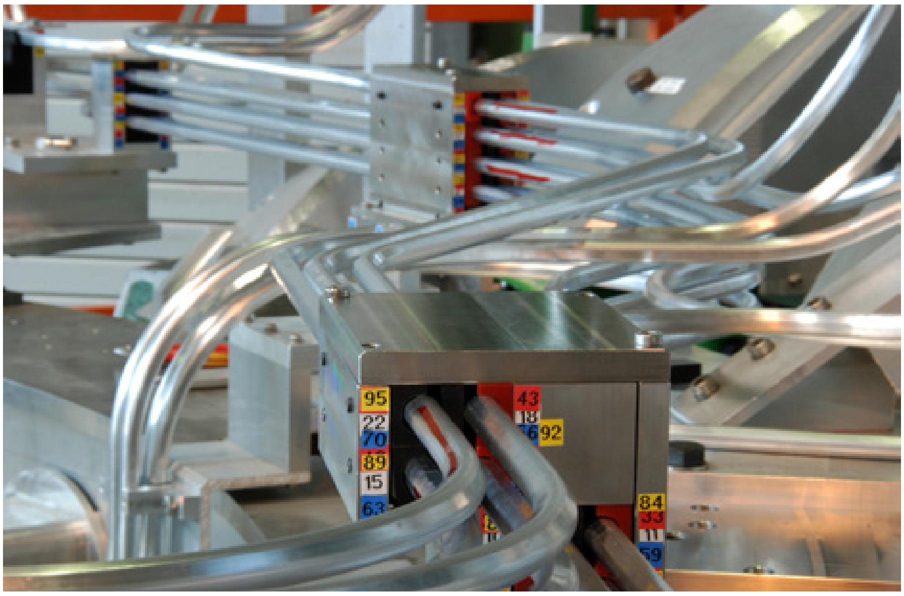
Research institutes:
Karlsruhe Institute for Technology
Industrial partner:
ODU Steckverbindungssysteme GmbH & Co. KG, (Mühldorf/Inn, Germany)
Contracts:
Development of a vacuum suitable High voltage bushing for ITER

RASI Maschinenbau GmbH, Illingen, Germany

The superconducting bus bar system – a colossal cable harness 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-dimensional 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 ín a road vehicle, for example, the shape of the connecting lines cannot be adjusted on site, since the superconducting cable is not flexible. They thus have to be prefabricated with a high accuracy of just a few millimeters. This made it necessary to build and calibrate a computer-controlled bending machine. The company RASI and the Forschungszentrum Jülich (FZJ) have jointly developed an instrument that allows bends to be realised in two directions. Normally, a variable bending direction is made possible by rotating the piece about its axis. Here, however, we are dealing with pre-formed parts of several meters in length, which, during rotation would swing freely in space, even below the 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.

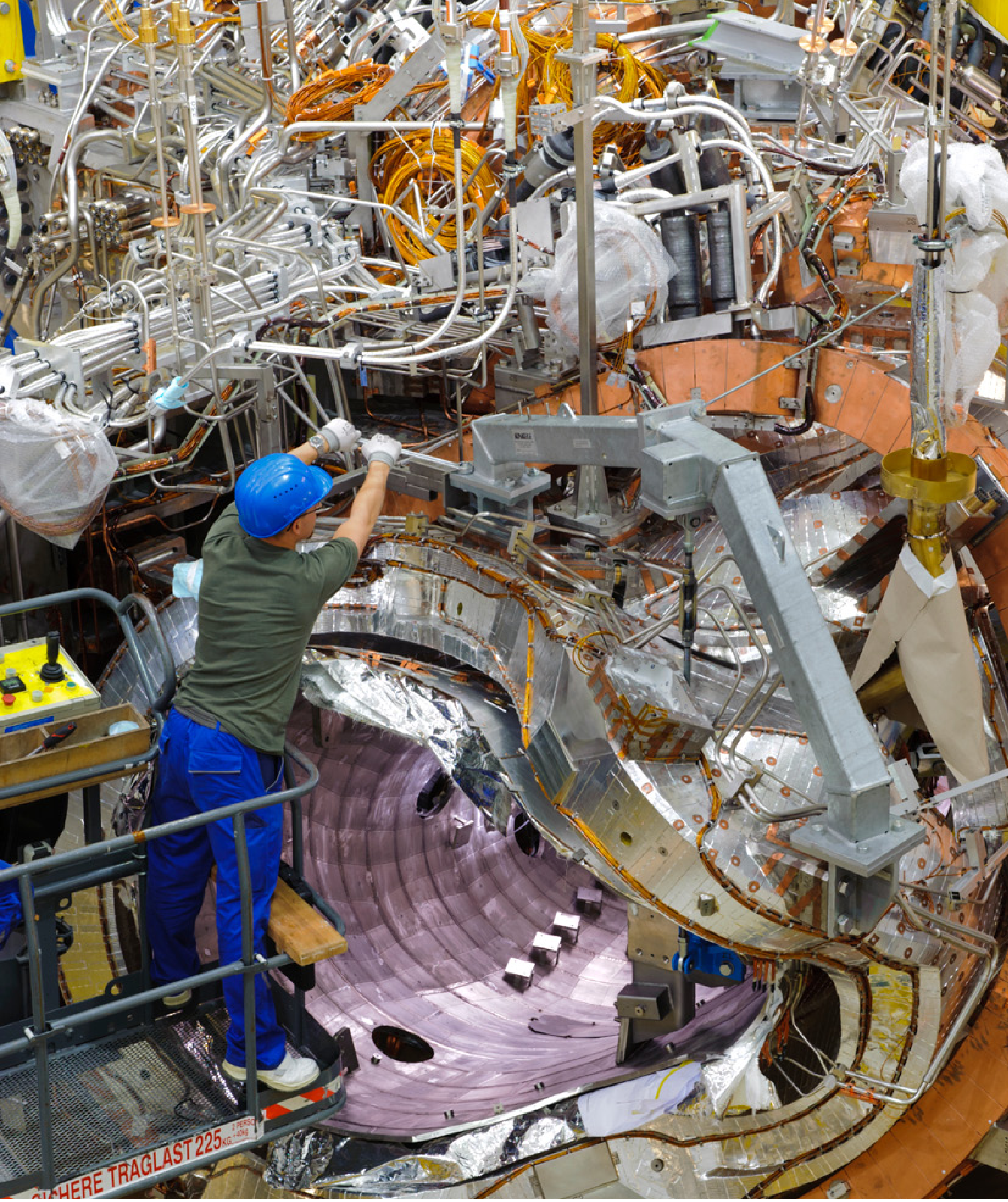
Geometry check of shaped superconductors



Facts:

Research institute:
Forschungszentrum Jülich GmbH
Industrial partner:
RASI Maschinenbau GmbH
(Illingen, Germany)
Contracts:
Development of a computer-controlled bending machine for two bending directions for use in the construction of the superconducting bus bar system of Wendelstein 7-X

The experience gained in developing this new machine will be valuable for future customer-specific developments by the manufacturer. The bending machine has already found interest from customers outside fusion research.



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