# Construction and Assembly of WENDELSTEIN 7-X

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**Abstract**
WENDELSTEIN 7-X (W7-X) is an optimised stellarator which shall demonstrate the reactor relevance of the HELIAS type magnetic configuration. The magnet configuration is produced by a set of 50 non-planar and 20 planar superconducting coils. These coils allow varying the magnetic configuration and studying the plasma in a wide range of parameters. The coil system is supported by a massive support structure and thermally protected by a cryostat.
Many components of W7-X are in an advanced stage of construction and several of the main components have been delivered. Following comprehensive trials to ensure that the specified accuracy can be met, assembly has started in April 2005.
The paper describes the status of construction and assembly and focuses on lessons learned during fabrication of the components.

Keywords: fusion devices, superconducting coils, cryostat

## 1. Introduction

W7-X is an optimised stellarator which shall prove the reactor relevance of the HELIAS-type magnetic configuration. The basic device consists of 50 superconducting non-planar coils which provide the standard magnetic configuration with a rotational transform $\iota=1$ at the plasma boundary. Additional 20 superconducting planar coils which are superimposed on the non-planar coils allow varying the rotational transform, the shear and the magnetic well to study the plasma in a wide range of parameters [1]. The basic operation parameters of W7-X are summarized in Table 1.

Physics diagnostics will explore plasma instabilities in the optimised magnetic configuration, turbulent transport, and steady state operation close to the operational limits. An open island divertor will allow studying the particle exhaust and the plasma wall interaction in compliance with a steady state ECR heating power of 10 MW. Achievement of the goals requires maintaining the symmetry of the magnetic field $\Delta B/B$ to typically $<10^{-4}$.

In order to meet the physics goals the magnet system of W7-X is composed of ten identical half-modules each comprising five differently shaped non-planar coils and two types of planar coils which are joined in a five fold symmetric arrangement. All components are designed for steady state operation. The design of the cooling water circuit limits operation at a maximum plasma heating power to 30 minutes. The coils are rigidly fixed to a massive coil support structure and interconnected by several inter-coil supports. Superconducting bus bars using the same conductor as that for the coils link all coils and connect the coils with the current leads.

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The tight tolerances on the field configuration impose severe constraints on the accuracy of the coil manufacture and all steps of assembly.

| | |
|---|---|
| major/minor plasma radius | 5.5/0.53 m |
| number of non-planar coils | 50 |
| number of planar coils | 20 |
| rotational transform | 5/6 – 5/4 |
| machine diameter | 16 m |
| machine height | 4.5 m |
| machine mass | 725 t |
| cold mass | 395 t |
| max. magnetic field on the axis | 3 T |
| magnetic energy of coils | 900 MJ |
| steady state heating power (ECRH) | 10 MW |
| add. heating power (ICRH + NBI) | 4 + 5 MW |

Table 1: Main design parameters of W7-X

The cold magnet structure is thermally insulated by a cryostat (Fig. 1). The cryostat is composed of the plasma vessel enclosing the plasma, the ports allowing observation and heating of the plasma, and the plasma-facing components allowing to control the energy and particle exhaust. Steady-state plasma heating is based on powerful ECR sources. In addition, the plasma temperature and density can be increased by pulses of ICR or NBI heating. The superconducting coils are energised with high current by dedicated supplies and kept at a temperature of about 4 K by a helium refrigeration plant. Safe operation of the magnet system is ensured by fast detection of quenches and subsequent shut-down.

## 2. Superconducting Magnets

The main components of the magnet system are the superconducting coils [2], the coil support structure, the inter-coil supports, the superconducting bus system, the current leads and the power supplies for the coils.

### 2.1. Superconductor

The coils are wound by a cable-in-conduit superconductor which is composed of 243 NbTi strands wound to a cable and enclosed by an aluminium jacket. The void within the cable is used for the helium coolant. By the end of 2005 the EAS/OCSI (formerly VAC/EM) consortium has delivered all of the 360 required conductors with typical lengths between 120 and 180 m. Some conductors showed broken strands. Following investigations at CRPP, Switzerland a maximum of one broken strand every 50 m could be accepted, provided that such conductors are only used for the outer turns, operating at a reduced magnetic field. Acceptance of the conductor also required to release the tolerance on the nominal void fraction of 37 % from ±1 % to ±2 % and to accept variations of the flow rate of up to ±20 %. The friction factors derived from flow rate measurements could not be correlated unambiguously with the void fraction.

### 2.2. Superconducting coils

The non-planar coils are being manufactured by the Babcock-Noell Nuclear (BNN)/Ansaldo Superconduttori consortium. Presently, 46 of the 50 winding packages have been delivered for coil assembly. In order to achieve the required magnetic confinement, winding of the conductor needs to be repeated with a precision of typically ±2 mm. Therefore, all winding packages are inspected at approx. 800 positions along the surface to check the compliance with the CAD model.
Small statistical deviations of the coils from their ideal shapes or non-symmetric alignments cause field perturbations with a periodicity different from the five-fold periodicity of

the device. Such perturbations may result in additional magnetic islands, ergodisation of existing islands, uneven load of the divertor target plates or enhanced particle losses. The analysis of the shape of the winding packages (Fig. 2) shows that absolute deviations from the CAD model are less than <3 mm and the reproducibility of the average geometry is well within the specified tolerance of 2 mm [3].
A Swedish subcontractor, Österby Gjuteri AB, has cast and machined all 100 half-shells of the coil casings from 316 LN stainless steel. The cast material features very good castability, weldability and good mechanical properties at cryogenic temperatures. During inspections with a linear accelerator (LINAC) casting failures such as shrinkages, pores and cracks were, however, discovered in areas, which have not been accessible to the standard X-ray inspection method before. Large defects required repair the small ones could be tolerated. Assembly of all non-planar coils is being done at BNN production site at Zeitz (Fig. 3). First the winding package is positioned between the two halves of the steel casings using four reference pins on each side of the winding package. Next the winding package is embedded in quartz sand and epoxy resin. After embedding, the interface areas of the casing are machined to the required precision on a five-axis CNC machine. The accuracy achieved is within 0.5 mm for reference pins and coil fixtures, 2 mm for the inner surface and 5 mm for the outer surface of the casings.
As a consequence of more detailed structural calculations the connections of the coils to the coil support structure as well as the interfaces to the inter-coil support elements had to be modified. This required reinforcement of welds, an increase of the number and size of the threads for the fixation bolts and re-machining of those areas where the coils contact each other along the inner side of the casing on a number of almost finished coils.
Cooling of the casing is provided by strips of highly conductive copper welded to the casing and soldered to stainless steel pipes. Finally, temperature and strain sensors are mounted. Eighteen quench detection tabs per non-planar winding pack provide redundancy and allow locating quenches within the coils precisely.

Manufacture of the 20 planar coils at Tesla Engineering is well advanced. All winding packages are ready, nine are embedded in the casings and three coils have been delivered (Fig. 4). During cold testing one casing loop showed a massive helium leak which was caused by pitting corrosion in the steel pipe due to residuals of an aggressive soldering flux. All cooling tubes were replaced by tubes with a larger wall thickness and the soft soldering technique was changed using non-aggressive flux. Refined structural calculations recently required reinforcing the casing against the out-of plane bending and shear loads by additional shear bolts. Integral leak tests are done using $SF_6$ as a tracer gas. Leaking gas is accumulated in a plastic bag around the coil and detected by laser spectroscopy to a sensitivity of $10^{-7}$ mbar*l*$s^{-1}$. To check the welds in the termination area with higher sensitivity local vacuum chambers and standard helium leak testing are applied.

During a rapid shut-down the coils induce voltages of up to ±4 kV which in the worst case could coincide with a degraded insulation vacuum. To check the electrical insulation under such conditions, each coil is routinely subjected to high voltage tests in a low vacuum environment. Several coils have shown electrical discharges at pressures between 1 and 100 mbar, where the applied voltage surpasses the Paschen minimum. In such cases the insulation was typically degraded by small voids, lack of epoxy resin, or insufficient electrical insulation of the quench detection wires.

### 2.3. Coil tests

After production all coils are tested under operational conditions at the Low Temperature Laboratory of Commissariat à L'Énergie Atomique (CEA) in Saclay. Meanwhile, seven non-planar and three planar coils were tested. The electromagnetic tests have been passed

without problems. Quenches are triggered at nominal current by raising the temperature of the helium inlet. They occurred at slightly higher temperatures than predicted giving some additional margin for the future operation of these coils [4].

### 2.4. Coil Support Structure

The coil support structure is being manufactured by the Spanish contractor Equipos Nucleares, S.A. (ENSA). It consists of ten identical sectors with a total weight of 72 t made from steel plates and cast extensions. The interfaces of the coil support structure are presently machined precisely at the Italian subcontractor Rovera. The planarity of the flanges as well as the position of the holes for the connecting bolts is within 0.05 mm, the holes for the bolts as well as the overall tolerance of the flange reference surfaces are accurate to within 0.1 mm (Fig. 5). To reach the highest accuracy for the interfaces to the coils the extensions of the two adjacent sectors of a module are machined in one run. Recent trials have demonstrated that the geometry is kept within tolerances even after repeated mounting and dismounting.

Ten cylindrical cryo-supports carry the support structure and provide the thermal barrier between the cold magnet system and the machine base.

Each coil is fixed via two support blocks to corresponding extensions on the coil support structure. These connections have to take electromagnetic loads of up to 4 MN and moments of up to 350 MNmm. Up to nine long studs from Inconel 718 with sleeves from the same material and special tensioners (Superbolt$^{TM}$) are used to achieve a corresponding high pre-stress and maintain it during cool-down to helium temperatures. Application of the necessary pre-stress of 800 MPa has been successfully verified during tests on mock-up connections [5].

### 2.5. Inter-Coil Supports

During operation the magnet system twists leading to complex deformations of the support structure and the coils. Originally a soft structure was favoured resulting in large excursions of the coils while still maintaining the symmetry. Comprehensive structural studies revealed that the connections between the coils and the support structure as well as some connections between the coils could not withstand the loads. Re-designing the inter-coil supports reinforced the structure and reduced the coil deformations as well as the loads on the connections to the support structure.

The lateral support elements which connect the coils along the outside forming a “helical belt” will be constructed from half boxes which are inserted and welded between the coils. A test programme was launched to assess the magnitude and reproducibility of the weld shrinkages and to predict the distortions of the magnets [6].

Narrow support elements are arranged along the inner side of neighbouring coils. They are exposed to loads of up to 1.5 MN and have to allow gliding of the coils of up to 5 mm and tilting of 1 degree. A comprehensive R&D programme was launched to investigate friction and stick-slip effects of different gliding pads under relevant loads and movements at ambient and cryogenic temperatures. Following these tests Al-bronze pads with $MoS_2$ coating have been selected. The pads will be kept by a pad holder, which in turn will be shrink fitted into appropriate recesses in the coils.

This pad design will also be adapted to other sliding supports located between the planar and the non-planar coils.

### 2.6. Bus Bars

Ten coils each are connected in series and with the current leads by a system of 121 superconducting bus lines with a total length of approx. 1100 m. Research centre Jülich (FZJ) is responsible for design, manufacture and assembly of the bus system. Only after rounding of the square Al-jacket the W7-X conductor could be bent to the required 3-D shape of the

individual bus lines. The bus lines of one non-planar coil type are routed bifilarly to avoid field errors. All lines are supported approx. every 300 mm by fixed or sliding brackets to avoid quenches. A 1:1 template of a module was set up and will be used to survey bending and to pre-install the single bus bars with individual lengths between 4 and 15 m.
The connection between the bus sectors requires approx. 300 disconnectable low-resistance joints. Tests at CRPP, Switzerland, showed resistances of about 50 pΩ well below the specified resistance of 5 nΩ. The design of the joint housing was improved to withstand pressures of up to 170 bars.

### 2.7. Current Leads

Fourteen current leads able to carry 20 kA each, connect the seven groups of superconducting coils to the corresponding power supplies. The current leads will contain $Nb_3Sn$ inserts at the cold end in order to achieve low idle current losses. The procurement of the current leads has started. All leads shall be tested at operational conditions prior to assembly.

### 2.8. Power Supplies and Quench Detection System

The five types of non-planar and two types of planar coils are energised by power supplies providing direct currents of up to 20 kA at voltages of up to 30 V. The Swiss contractor, ABB, selected the concept of twelve-pulse rectifiers to ensure that the currents are stabilised with an accuracy of $2x10^{-3}$.
Fast and reliable discharge of the superconducting magnets in case of quenching is realised by fast circuits which short-circuit the coils and dump the magnetic energy to nickel resistors. These resistors feature a high heat capacity and a strong increase of the resistance with temperature which keeps the switching voltages low and shortens the slow-down time during a rapid shut-down. All seven power supply units have been commissioned, satisfying the technical specification. The quench detection system is developed in co-operation with the research centre Karlsruhe (FZK). The system consists of nearly 400 quench detection units which permanently check the differential voltages across double layers of all coils and across all sectors of the bus system. The system has to reliably detect millivolt signals in a broadband noise environment. Signal amplifiers which can withstand the high voltages induced during a quench have been successfully tested.

## 3. Cryostat

The cryostat provides thermal protection of the magnet system and gives access to the plasma. Its main components are the plasma vessel, the outer vessel, the ports and the thermal protection. German Deggendorfer Werft und Eisenbau GmbH (MAN DWE) are responsible for manufacturing the plasma vessel, the outer vessel and the thermal insulation. Swiss company Romabau Gerinox is fabricating the ports.

### 3.1. Plasma Vessel

The plasma vessel is composed of ten half-modules which are divided into two sectors to allow stringing of the innermost coil during assembly. Construction of the plasma vessel required 200 steel rings to be bent to the designed shape and carefully welded to represent the changing cross-section of the vessel with an accuracy of 3 to 7 mm. Vacuum tightness of the welds was checked by an integral helium leak test of the vessel segments prior to cutting the holes for the ports. Water pipes around the vessel allow control of its temperature during plasma operation and for bake-out at 150 °C. Manufacture of all half-modules has been completed (Fig. 6).

### 3.2. Outer Vessel

The outer vessel is assembled from five lower and upper half-shells and will have 524 openings for ports, supply lines, access ports, instrumentation feedthroughs and magnetic diagnostics. All upper and lower main bodies of the half-shells of the outer vessel have been manufactured. Cutting of the openings of the first module is finished and several of the domes have been welded.

### 3.3 Ports

A total of 299 ports are used to evacuate the plasma vessel, for plasma diagnostics and heating, as well as for supply lines and sensor cables. The cross sections of the ports range between 100 mm circular up to 400x1000 mm² square and are equipped with bellows to compensate deformations and displacements of the plasma vessel with respect to the outer vessel. All ports are surrounded by water pipes to control their temperature. By the end of 2005, 261 ports will be delivered to IPP. Recent tests by the manufacturer on the large rectangular port have shown significant differences from extrapolations using the EJMA code for the spring constants. Whereas the axial spring constant is described correctly by the code, the lateral and angular spring constants are underestimated by a factor of 2 to 4.

### 3.4. Thermal Insulation

Efficient protection of the cold components against thermal radiation is achieved by actively cooled shields, high vacuum, and 20 layers of reflecting foils. In order to achieve the required narrow tolerances of ± 2 mm a novel technique, applying epoxy impregnated glass fibre panels with integrated copper meshes was developed. This way also a good heat conductivity along the shield could be achieved. The copper meshes are intersected to reduce eddy currents. The shields are kept at temperatures between 40 K and 70 K by cold helium gas. The cooling tubes are attached to the shield by copper braids (see also Fig. 6). Sixteen of twenty panels have meanwhile been mounted on the first half-module of the plasma vessel. Tests of the multilayer insulation have shown extremely low losses of 0.67 resp. 0.93 W/m² [7] for non-compressed resp. compressed multi layer insulation with realistic overlaps.

### 3.5 In -Vessel Components

The in-vessel components comprise divertor target plates and baffles for energy and particle control, panels and heat shields to protect the wall against plasma radiation, control coils to modify the magnetic configuration at the plasma boundary, water supply lines for heat removal, and cryo-pumps to control the neutral gas density during high-density plasma operation [8]. The company Plansee AG, Austria is manufacturing the target elements, MAN DWE the wall protection panels and BNN the control coils. Assembly of the target modules from target elements as well as fabrication of the baffles, the heat shields, the cryo-pumps and of the supply lines is performed by IPP.

Several areas with different heat loads can be distinguished. The divertor horizontal and vertical target modules will experience power fluxes between 1 to 10 MW/m$^2$. The baffles, which prevent the neutrals from re-entering the receive power fluxes of up to 0.5 MW/m$^2$. The wall is subject to neutral particles and plasma radiation in the range of 0.1 to 0.3 MW/m$^2$. To keep the reflux of impurities to the plasma within acceptable limits all plasma-facing surfaces are covered with low-Z material. The target plates are armoured by CFC tiles, the baffles are covered by graphite tiles and the wall protection will be coated with boron carbide.

Ten divertor targets with surfaces of 1.9 m² each are composed of 890 segments which closely follow the 3-D shape of the plasma boundary. For these areas 8 mm thick CFC tiles made of SEPCARB® NB31 from SNECMA Propulsion Solide, France are used and joined with the water-cooled CuCrZr heat sink either by electron beam welding or hot isostatic

pressing [9]. Approx. 550 kg of CFC for the series blocks have been produced, but show a reduced tensile strength in the direction perpendicular to the surface. The selected manufacturer of the target plates, Plansee AG, Austria is checking the bonding process with pre-series elements to decide whether the degraded material can nevertheless be used. The target elements are tested up to 12 MW/m² in the GLADIS test facility [10].
Numerical modelling of the heat load showed that the power distribution on the targets is rather localized even during different magnetic equilibria. Therefore, the middle part of the horizontal target plate needs only to be protected against loads up to 1 MW/m² using the same technology as for the baffle plates.
The baffle plates cover an area of about 30 m² and are composed of 2900 baffle elements. The elements are made from 20 mm thick fine grain graphite elements which are clamped to a water-cooled CuCrZr alloy heat sink. Technologies to bend and fix the stainless steel cooling tubes to the CuCrZr support have been developed and qualified.
About half of the 130 m² large surface of the plasma vessel is covered by double-walled stainless steel panels with integrated water-cooling. These panels will be coated with $B_4C$ to improve the plasma-wall-interaction. Prototypes of such panels have been produced with the required accuracy by MAN DWE (Fig. 7). The inner wall, which is close to the plasma is protected by graphite tiles using the baffle design principle.
Ten control coils will be installed behind the baffle plates. These coils will be used to correct small field errors at the plasma edge, to optimize the position and extent of the islands and dynamically sweep the power across the target plate.
Each coil is made of eight turns of a hollow copper conductor and is water cooled. BNN is manufacturing the coils and will deliver the first unit by the end of 2005.
These coils will be supplied individually by power supplies with a DC current of 2.5 kA at voltage up to 30 V that can be modulated at frequencies up to 20 Hz. The power supplies have been built by the Spanish company JEMA, Spain and successfully tested.

Vacuum pumps with an effective capacity of 37 m³/s are required to evacuate the plasma vessel, to control the density of auxiliary gases injected into the divertor chamber and to pump neutral particles. Additional cryo-pumps located behind the target plates allow to increase the pumping capacity for hydrogen and deuterium to 100 m³/s during high-density plasma discharges. The cryo-pumps are composed of a cryo-panel cooled with liquid helium, a Chevron baffle, a reflector cooled with liquid nitrogen and an additional water cooled baffle. The main parts of the cryo-pumps have been fabricated in the IPP workshop.

## 4. Assembly

Half-module assembly starts with stringing the innermost coil (type 3) across one sector of the plasma vessel. Special handling tools were constructed to move and rotate precisely the non-planar coils with masses of up to 6 t as well as the planar coils across the plasma vessel. When the two sectors of the plasma vessel half-module are welded together, part of the thermal insulation is mounted. Next the other coils are strung and fixed, the thermal insulation being subsequently completed. When all five non-planar and two planar coils are mounted a sector of the coil support structure is moved against the coils and fixed with the coils [11].
To prepare assembly individual mounting stands of the half-modules and modules of the magnet system have been set-up. Special lifting and transportation tools for half-module and module transportation were constructed. The machine base, which consists of a stable pentagon with five cantilevers resting on five massive supports, was ordered.
The metrology team has been strengthened and is meanwhile routinely applying laser tracking, laser scanning and photogrammetry techniques to survey and measure the complex 3 D surfaces of all W7-X components and to control the assembly process.

Assembly trials have demonstrated that the coils can be adjusted in space and re-positioned with an accuracy of 1.5 mm. Welding trials on a dummy sector of the plasma vessel showed that the predicted shrinkage of 2 mm can be kept allowing precise adjustment of the vessel during assembly. Particular emphasis was given to trials of the narrow support elements. These elements have to be fitted after stringing of neighbouring coils between the inner sides where access is very restricted (Fig 8). Tests were performed to determine the exact dimensions of the pad holder by a silicon casting technology and to train shrink fitting the pad holder into the coil casing. Welding of the bus bars to the aluminium conductor terminals of the coils was intensively trained to ensure a good weld quality under the very restricted welding positions in W7-X.
All W7-X components need to be prepared before they can be released for assembly. This preparation includes checks of the dimensions and of instrumentation, assembly of connections and additional supports and protection of parts during assembly. Detailed working procedures were set-up and checked during preparation of the first components.

Assembly of the machine started in April 2005 by stringing the first coil across the plasma vessel. Meanwhile two coils are mounted and another two coils are being prepared for assembly. Following the present schedule the mechanical completion of the basic device is planned for the middle of 2011 and plasma operation shall start in the middle of 2012.

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Table 1: Main design parameters of W7-X

| | |
|---|---|
| major/minor plasma radius | 5.5/0.53 m |
| number of non-planar coils | 50 |
| number of planar coils | 20 |
| rotational transform | 5/6 – 5/4 |
| machine diameter | 16 m |
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| machine mass | 725 t |
| cold mass | 395 t |
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| magnetic energy of coils | 900 MJ |
| steady state heating power (ECRH) | 10 MW |
| add. heating power (ICRH + NBI) | 4 + 5 MW |

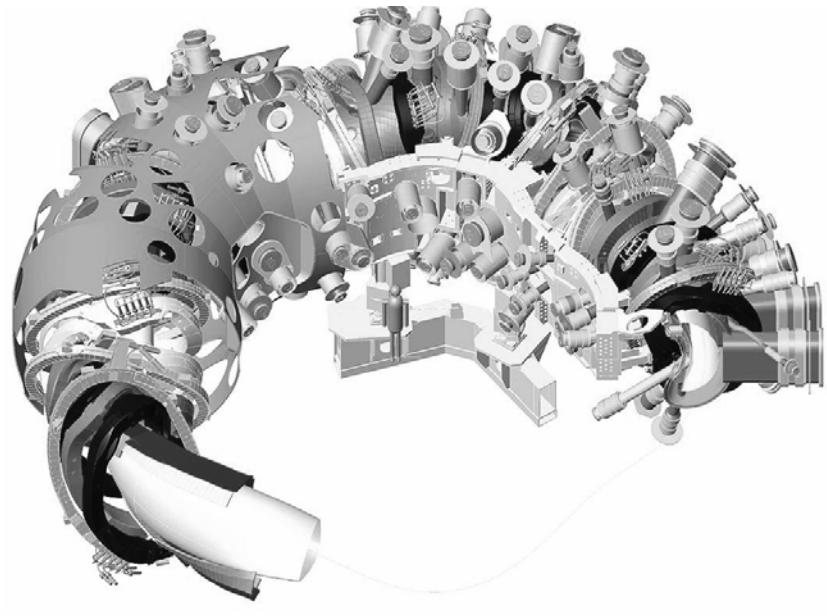

Fig. 1: 3-D view of the W7-X basic device

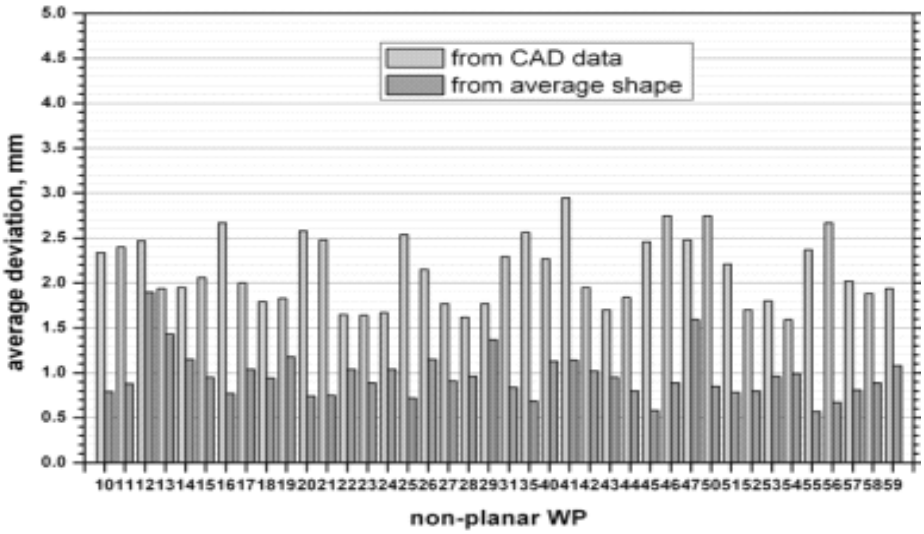


Fig. 2: Accuracy of the winding package of the non-planar coils

Fig. 3: Non-planar coil

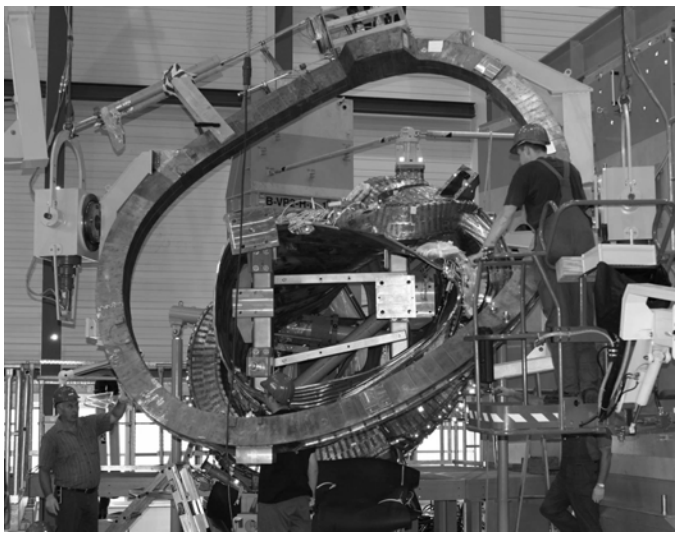

Fig. 4: Planar coil during assembly

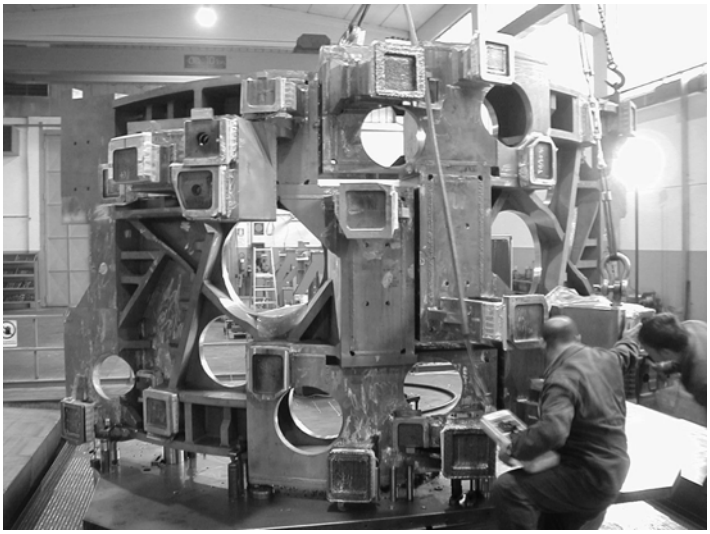

Fig. 5: Two sectors of the coil support structure during trial assembly


Fig. 6: Plasma vessel segments at MAN DWE

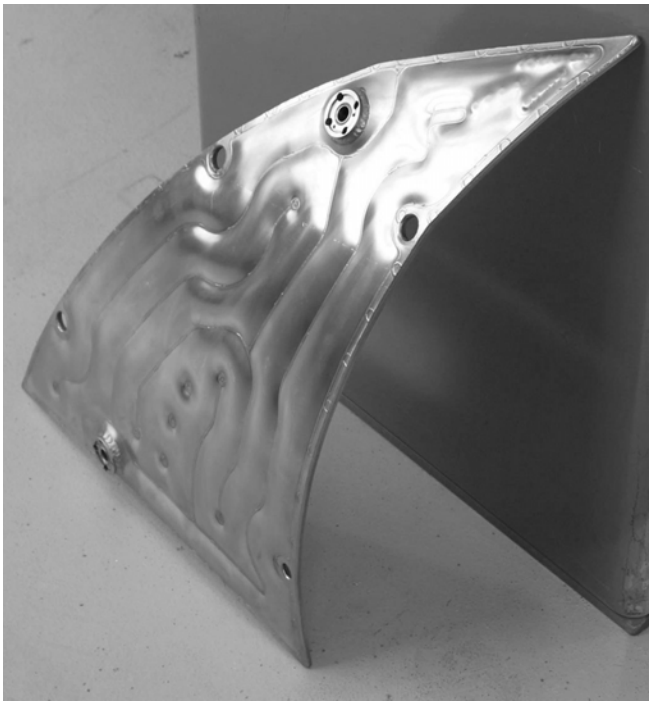

Fig. 7: Prototype panel of the wall protection

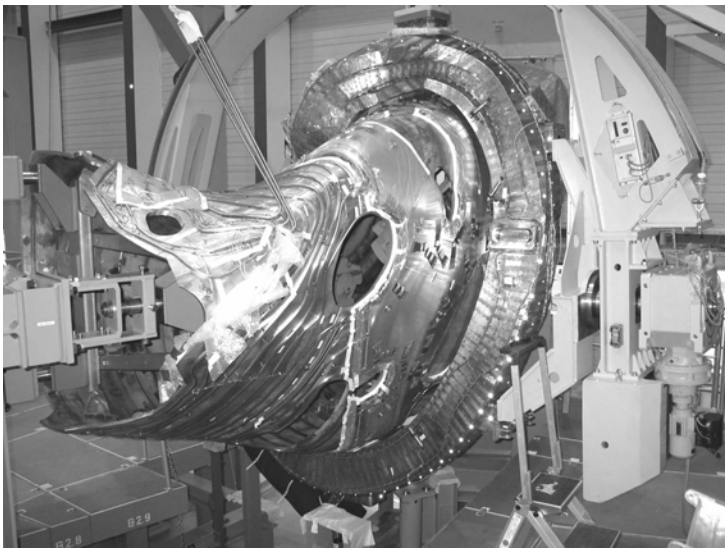

Fig. 8: Assembly of the coils and the plasma vessel