Status of WENDELSTEIN 7-X Construction

M. Wanner and the W7-X Team

Max-Planck-Institut für Plasmaphysik, EURATOM Association, Teilinstitut Greifswald, Wendelsteinstraße 1, D-17491 Greifswald, Germany

e-mail contact: manfred.wanner@ipp.mpg.de

Abstract. WENDELSTEIN 7-X (W7-X) shall confirm the favourable plasma properties and the high density and beta limits of the helical advanced stellarator and demonstrate steady-state operation. The magnetic configuration of W7-X is characterised by a set of 50 non-planar and 20 planar superconducting coils. The magnet system will be manufactured and assembled to a precision of a few millimetres and maintain its symmetry during cool-down to cryogenic temperatures. Power supplies allow to adjust the magnetic field with a precision of a few mT and safely dump the magnet energy in case of a quench. The plasma vessel gives maximum space for the plasma and is adjusted symmetrically w.r.t. the plasma by dedicated means. Steady-state heating is achieved by 10 MW ECR. Energy and particles are controlled by a continuously working divertor. All plasma-facing surfaces are covered by CFC, graphite and B_4C. The paper reviews the status of construction and describes details of the design.

1. Introduction

W7-X is the follow-up of WENDELSTEIN 7-AS and is presently being built at Greifswald. The standard magnetic configuration of W7-X is the result of an optimisation of several physics criteria [1] and is characterised by a magnetic induction of 2.5 T along the plasma axis, an iota of 5/5 at the plasma boundary, a shear of about 15 % and a magnetic well of typically 1 %. The magnetic configuration is completely defined by the current distribution in 50 non-planar coils which are arranged in five periods. Additional 20 planar coils allow to

TABLE I: MAIN DESIGN PARAMETERS OF W7-X

major plasma radius	5.5 m
minor average plasma radius	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	425 t
max. magnetic field on the axis	3 T
magnetic energy of coils	600 MJ
heating power($1^{st}/2^{nd}$ stage)	15/30 MW
plasma pulse length	30 min operation at 10 MW ECR-heating, 10 s at full NBI and ICR heating power

vary iota between 5/6 and 5/4 or to modify the magnetic shear. The magnetic induction can be increased up to 3 T on the axis to allow off-axis deposition of 140 GHz radiation. Steady-state operation is achieved by superconducting coils and 10 MW ECR heating. The flow of energy and particles is controlled by a continuously working open divertor which makes use of the island structure along the helical edge of the plasma. Plasma temperature and density can be increased by 4 MW of ICR and 5 MW of NBI heating. To reach the predicted ß-limit of 5 % at densities of up to $3x10^{20}$ m^{-3} the capacity of the NBI heating systems will be upgraded to 20 MW at a later stage.

The overall design parameters of W7-X are set by the physics requirements of the experiment and are shown in Table 1. The main components of the stellarator are the superconducting magnet system to confine the plasma, the cryostat to insulate the cryogenic parts, ports to observe and heat the plasma and to supply the plasma-facing components with cooling water, and in-vessel components to control the energy and particle exhaust. A CAD view of the basic machine is shown in Fig. 1.
The superconducting coils are energised with high current by dedicated power supplies and kept at cryogenic temperatures by a helium refrigeration plant. The plasma heating systems are supplied with high voltages of up to 130 kV. A total input power of about 48 MW is required to operate the magnet system, supply the heating systems, and provide power for cryogenic refrigeration.

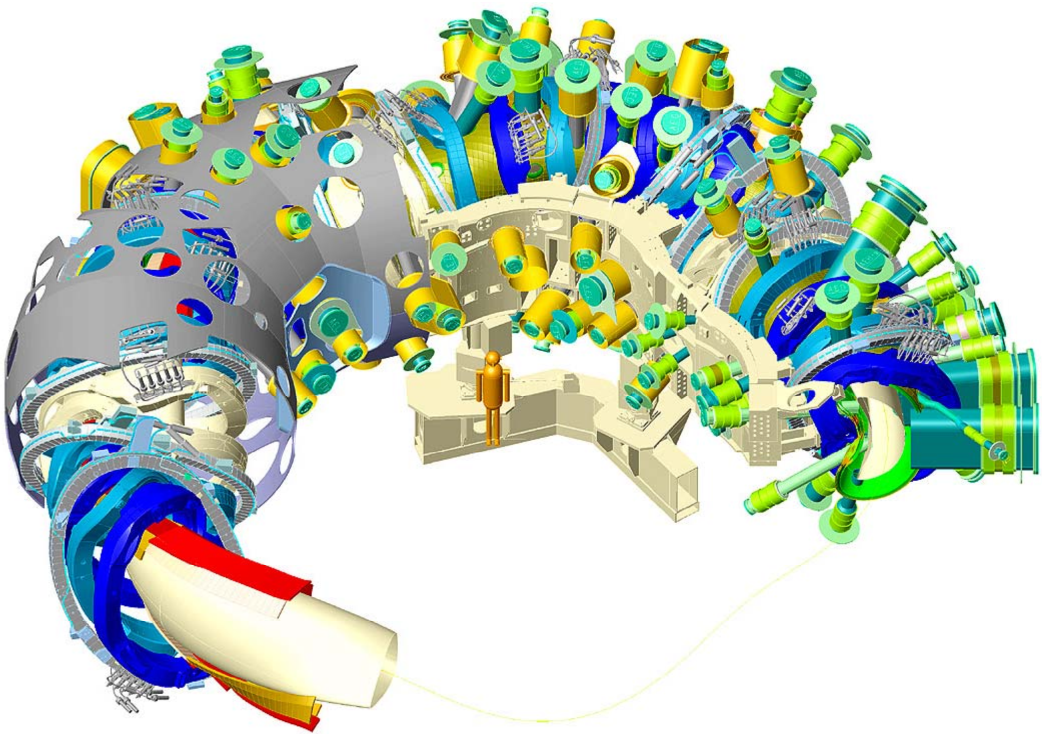

FIG. 1. CAD view of WENDELSTEIN 7-X .

2. Magnet System

The superconducting coils of W7-X are wound from a cable-in-conduit conductor, which is composed of 243 strands enclosed by an aluminium jacket. Strands with the required critical current are being manufactured by the VAC/EM consortium. The consortium encountered, however, unexpected difficulties with cabling the ropes, jacketing the cable, and verifying the specifications of the conductor. Several iterations were required to keep the void fraction within the agreed range between 35 - 39 % and the minimum wall thickness at 2 mm. Although series production was released already in May 2001 only about 1/5 of the total amount of conductor is delivered up to now due to shortfalls in the test facilities. The delay of the conductor has meanwhile a serious impact on production of the non-planar and planar coils and hence on the overall project schedule.

The Babcock-Noell Nuclear (BNN)/Ansaldo consortium is responsible for the design and manufacture of the 50 non-planar coils. To keep the required accuracy of the coils, winding forms with an accuracy of a few tenth of a millimetre were set up. Winding of the different types of coils is being performed on three parallel winding lines at Ansaldo and two parallel winding lines at BNN's subcontractor ABB. Winding starts with preparation of the conductor by straightening, sand-blasting, and insulating with glass tape. For each winding package 108 turns are wound to form six double layers. The double layers have typical lengths of 150 to 180 m and are electrically connected in series and cooled in parallel by single phase helium. Finally the aluminium jacket is hardened at approx. 170 °C, the winding package is impregnated, and the whole winding package is surrounded by ground insulation as shown in Fig. 2. Measurements of the first winding package showed that the contour is within the specified tolerance band of +5/-3mm.

FIG. 2. Winding package of a non-planar coil (by courtesy of BNN).

Meanwhile four winding packages were wound and the first non-planar coil is being integrated in its casing. In order to allow assembly of the coils the coil casings need to be fabricated as two halves. The shape of the halves of the stainless steel casings is realised by a casting technique followed by a heat treatment and precision machining.

Assembly of the non-planar coils has to consider that during cool-down to cryogenic temperatures the winding package of the coils tends to shrink more than the steel casing which would produce excessive stress on the conductor. For that reason the casings are heated to about 120 °C during embedding whereas the winding package is kept at ambient temperature. Cooling of the coil casings is achieved by four helium pipes around the circumference which are coupled to the steel casing by sheets made of high conductivity copper. In order to reduce eddy currents in the casings during rapid shut-down of the magnetic field, the copper sheets are segmented into strips.

Design and manufacture of the 20 planar coils is performed at Tesla Engineering. The planar coils follow the same construction principle as the non-planar coils with the main difference that only 36 turns have to be wound to an almost circular shape. This allows standard winding techniques to be applied and to manufacture the casings from plate material.

The double layers of each superconducting coil need to be electrically connected in series by low-resistance joints. To limit the ohmic heat at cryogenic temperatures, the resistance of a single joint must be below 1 nΩ. Prototypes tested by Ansaldo and Tesla showed that this stringent requirement can be met. In order to insulate the electric circuits of the windings against the helium pipes, special voltage breakers were designed and successfully tested at cryogenic temperatures.

All superconducting coils will be subjected to an acceptance test at nominal operation conditions at the Low Temperature Laboratory of CEA in Saclay. The test facilities have been prepared and successfully tested using the DEMO coil.

The coils need to be kept at their precise position during assembly, cool-down and operation where they will be subject to local electromagnetic forces of up to 3.6 MN. Each coil is therefore fixed through two extensions to a massive support structure which consists of ten identical sectors with a total weight of 72 t. The sectors (see Fig. 3) will be joined by screws to span a central pentagon. The coil support structure is made from steel plates and precisely cast steel elements for the coil fixtures at the Spanish contractor Equipos Nucleares S.A. Precise fitting of the flanges between the sectors requires machining to a precision of a few tenths of a milli

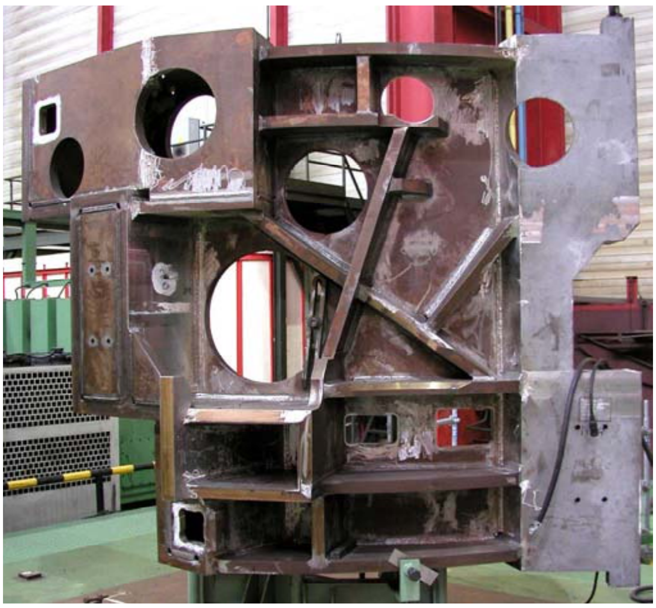

FIG. 3. Coil support structure during manufacture (by courtesy of ENSA).

metre. Since the coil support structure needs to be kept at the same low temperature as the coils helium-cooling pipes are contacted on the surface of the structure.

All 10 coils of one type are connected in series and powered by seven power supplies with 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 will be stabilised to an accuracy of $2x10^{-3}$. Design of the power supplies allows to adjust the magnetic induction with an accuracy of 30 mT. The field ripple produced by the power supplies is of the order of 2 mT at a frequency of 600 Hz and hence has a negligible effect on the plasma confinement. Magnetic induction can be varied up to 5 mT/s to allow for scans during long plasma discharges.
For fast and reliable discharge of the superconducting magnets in case of a quench the coils are short-circuited and the magnet energy of up to 600 MJ is dumped to nickel resistors within 5 s. These resistors feature a high heat capacity and a strong increase of the resistance with temperature. The switching voltages can thus be kept low. The results of tests with arc shoot breakers and a newly developed ignition device are in accordance with the specification. The first unit will be delivered in autumn 2002.

Fourteen current leads are required to connect the seven groups of superconducting coils with the power supplies. A study showed that conventional current leads designed for lower than nominal current, but operated under overload conditions, are superior to leads based on high-temperature superconductors, which were considered as an alternative. Designing the current leads for lower current reduces the stationary heat conduction during the long idle current period at the expense of slightly higher heat loads during peak current operation.

A widely ramified superconducting bus system connects the 14 current leads with the seven groups of coils and connects the ten coils of each type. The bus is made of the same cable-in-conduit conductor as the coils. Routing of the bus lines is performed in a bifilar way in order to reduce stray magnetic fields, which would have a negative impact on the magnetic configuration of W7-X. Five bus subsystems comprising some 1000 m of conductor need to be prefabricated and assembled using some 200 low-ohmic joints.

Ten copper control coils, which are wound with eight turns of a hollow copper conductor and cooled by water, will be installed in the plasma vessel behind the baffle plates. They are used to correct minor field errors, influence the extent and location of the magnetic islands, and allow the power deposition area to be swept across the target plates. Each coil can be supplied with a direct current of 3 kA at a maximum voltage of 30 V, which can be modulated at frequencies of up to 20 Hz by dedicated power supplies. Ten power supplies have been constructed and mounted by the Spanish contractor, JEMA.

3. Cryostat

The thermal protection of the coil system is provided by the cryostat. Its main components are the plasma vessel, the outer vessel, the ports, and the thermal insulation.

The German company, Deggendorfer Werft und Eisenbau GmbH (DWE), is responsible for manufacturing the plasma vessel and outer vessel. A major challenge of the design of the plasma vessel was to optimise the shape in order to give maximum space for the plasma while keeping the necessary clearance to the cold coils. The plasma vessel is being constructed from steel rings bent precisely to the required shape and carefully welded together to keep the

surface of the vessel within local tolerances of 3 mm as shown in Fig. 4. Water pipes around the outside of the vessel allow bake-out at 150 °C and control of the vessel temperature during plasma operation. The openings for the ports are precisely cut by a water jet technique. Delivery of the first sectors of the plasma vessel is planned for the beginning of 2003.
The plasma vessel is mechanically supported from below by 15 adjustable supports. Additional supports allow to adjust the horizontal position of the plasma vessel w.r.t. the magnetic configuration within a range of ±5 mm.

FIG. 4. Assembly of a sector of the plasma vessel (by courtesy of DWE).

Manufacture of the outer vessel has started. To allow assembly of the cryostat the sectors of the outer vessel need to be divided horizontally and delivered as half-shells. The design considered approx. 1,200 openings for ports, manholes, and feedthroughs.
The 309 ports of the cryostat are being manufactured by the Swiss company, Romabau. Dimensions of the ports range from 100 mm circular diameter up to 400x1000 mm^2 rectangular. Small movements during thermal expansion of the plasma vessel are compensated by steel bellows. Manufacture of the first ports has started.
Efficient insulation of the superconducting coils requires careful reduction of heat conduction and thermal radiation by high vacuum and many layers of reflecting foils. Efficiency of the thermal protection is improved by metallic shields which cover all areas at ambient temperature. The shields are kept at temperatures between 40 K and 70 K by circulating cold helium gas. The call for tender has been issued.

4. In-Vessel Components

With respect to plasma interaction three different types of surfaces can be distinguished in W7-X: The divertor target plates are hit predominantly by hot particles from the plasma and have to withstand heat loads of up to 10 MW/m^2. Baffles, which influence the fluxes and density of neutralised particles in front of the target plates, need to be designed for heat loads of 0.5 MW/m^2. The wall protection of the plasma vessel is mostly interacting with neutral particles and radiation from the plasma boundary and has to withstand heat loads of up to 0.2 MW/m^2. To control the reflux of impurities to the plasma all plasma-facing surfaces have

to be covered with low-Z material. The components have been specified and the call for tender is in progress (see reference [2] for more details).
Vacuum pumps are required to evacuate the plasma vessel, to pump out neutral particles, and to control the density of auxiliary gases injected into the divertor chamber. Turbomolecular pumps will provide an effective pumping speed of 42.000 l/s for H_2. Since operation of the turbomolecular pumps is restricted to typically 5-7 mT positioning of the pumps and magnetic shielding are being detailed. During high density plasma operations the pumping speed can be increased up to 150.000 l/s by cryo-pumps.

The target plates will be controlled and protected by uncooled bolometers for target thermography and thermometry, water flow control, and measurement of thermo-currents.

5. System Control

W7-X will be controlled by a master control system with local controllers for all subsystems such as magnets, cryogenics, heating systems, diagnostics, and data acquisition. The local controllers will run automatically according to predefined routines and parameters, which will be set from the master control system whenever the units have to operate together. In order to structure operation of the experiment, machine, and related subsystems, all periods of operation will be divided into segments of variable duration. A "segment programme" defines the operational rules and parameters which determine the state and activity of each unit in use. Programmable Logic Controllers will be used mainly to control those machine components and diagnostic systems which do not require short response times. Segment processing and fast feedback control, which require data processing in real time, will be performed by PCs running the VxWorks real-time operating system. Precise timing and synchronisation of all actions on a time scale of microseconds are based on a Trigger-Time-Event system with a central clock running at 50 MHz, a message manager, and signal distribution along glass fibres.

6. W7-X Assembly

Basically, assembly of the stellarator is performed by joining five prefabricated modules to a torus. Each module is composed of two half-modules which are mirror-symmetric to each other. A paramount prerequisite for proper confinement of the plasma is the exact fivefold symmetry of the magnetic field. As a consequence, errors in the shape of individual coils or deviations from their ideal position which break the symmetry must be smaller than 0.1 mm on a scale of one metre. Such small tolerances require high precision during manufacture of the components and assembly.
The assembly sequence starts with stringing the coils across the plasma vessel. A special handling tool was constructed to move and rotate the non-planar coils with masses of up to 6 t precisely across the plasma vessel. A second coil-handling tool will be used to handle the planar coils. The small clearance between the coils and the plasma vessel means that the plasma vessel of each half-module has to be divided to allow the innermost coil to be strung across the vessel. When the vessel is welded together, part of the thermal insulation is mounted.
Next, two half-modules are joined in a second assembly device. Hydraulic cylinders allow precise alignment of the half-modules in all directions. The sectors of the coil support structure are bolted, the plasma vessel is welded, and the bus bar and cooling lines are connected.

Assembly is continued by transporting the modules into the torus hall and lifting them into the insulated lower half of the outer vessel. After integration of supports, the outer vessel is closed and some sixty ports and the in-vessel components are installed. The five modules of W7-X are moved to their final location on a central support ring which rests on five steel supports. Finally the sectors of the plasma vessel and the outer vessel are welded. The temporary supports are removed, some remaining ports are mounted, the thermal insulation is completed, and the final bus connections are made.

7. Heating Systems

Heating of the plasma is achieved by ECRH, ICRH and NBI. ECRH is the main heating system and is being developed and built by Forschungszentrum Karlsruhe (FZK) as a joint project with IPP, Institut für Plasmaforschung (IPF) Stuttgart, and CRPP Lausanne. To achieve 10 MW steady-state heating power at 140 GHz ten gyrotrons with 1 MW each will be required. A pre-prototype ('Maquette') was built by the French company, Thales, and tested successfully at FZK reaching a maximum RF output power of 1 MW during pulses of 10 s. Operating the tube with a collector voltage depression recovered energy and increased the output efficiency to almost 50 %. Pulse lengths could be increased up to 180 s at 0.47 MW of output power. After evaluation of the test results and inspection of the Maquette a further prototype was built. During recent tests at FZK with this prototype an RF power of 0.95 MW was reached and the pulse length could be increased to 1000 s.
The transmission system as well as the ECRH-specific HV system are designed by IPF Stuttgart. Transmission of the RF power is performed quasi-optically. All wave guiding elements of the matching optics are actively cooled to allow for steady-state operation.

The ICRH system shall deliver 2x2 MW and work in a frequency range of 25 to 76 MHz to allow ^{3}He and H minority heating in D plasmas, mode conversion heating in H/D mixtures, and second-harmonic heating of hydrogen. A transmission line resonator has been designed using the 50 kW steady-state capability of an ASDEX Upgrade generator. This generator is sufficient to achieve locally the high voltages and currents occurring during full power operation in W7-X and to test technologies for active cooling of components, movable contacts, and ceramic spacers.

NBI is planned in W7-X for bulk heating of the plasma in the high-density, high-ß regime. A neutral beam power of 5 MW for 10 s using 60 keV deuterium injection will be available in a first stage using injector boxes of the ASDEX Upgrade type. The system can be upgraded in future to 20 MW for 15 s by adding three more beam sources in the beam injector boxes and replacing the titanium evaporator pumps with cryo-pumps.

[1] BEIDLER, C., et al., Physics and Engineering Design for Wendelstein 7-X, Fusion Technology **17** (1990) 148.
[2] RENNER, H., et al., Divertor Concept for the Wendelstein 7-X Stellarator: Theoretical Studies of the Boundary and Engineering (No. of Paper FT/P2-04), 19th IAEA Fusion Energy Conf., Lyon 2002.