Wendelstein 7-X, Overview and Status of Construction

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Abstract—The line of the WENDELSTEIN stellarators developed in IPP is being continued with a superconducting device, Wendelstein 7-X. This fully optimised stellarator which shall demonstrate the reactor potential of the Helias-type stellarator, is presently under construction in the Greifswald branch institute of IPP. Manufacturing of the W7-X components has progressed well over the last years, and assembly of the device has started early in 2005.

Keywords—W7-X stellarator; superconductor; magnet system; vacuum vessel; in-vessel components

I. INTRODUCTION

Stellarators are a concept for confining toroidal plasmas with magnetic fields generated exclusively by external coils. Therefore, without the net toroidal current required in tokamaks, they are intrinsically capable of steady state operation and can be operated without disruptions and without a need for external current drive systems. The disadvantages of classical stellarators have been overcome by the computational stellarator optimization in the last two decades. The line of the WENDELSTEIN stellarators developed in IPP has led to the first Advanced Stellarator, W7-AS, operated until 2002. W7-AS was a medium-sized, low-shear stellarator, partially optimised to have improved equilibria with a Shafranov shift reduced by a factor of 2 as compared to a classical stellarator. It used, for the first time, modular coils, i.e. the toroidal and poloidal field components were produced by a single set of non-planar coils. W7-AS clearly demonstrated the viability of the advanced stellarator [1].

II. DESIGN PRINCIPLE OF WENDELSTEIN 7-X

Wendelstein 7-X (W7-X), presently under construction in the IPP branch-institute in Greifswald [2], is a fully optimized stellarator. Its optimisation is based on the concept of quasi-isodynamicity [3]. The criteria to select the final magnetic configuration have been the following [4]:
- high quality vacuum magnetic surfaces
- good finite-\(\beta\) equilibrium properties
- good MHD stability properties
- small neoclassical transport in the “long mean free path (lmfp) regime”
- small bootstrap fraction in the lmfp regime
- good collisionless alpha particle containment
- feasibility of modular coils.

The W7-X configuration has a five-fold symmetry and is described by a rotational transform \(t/2\pi\) of about 1 (0.72 < \(t/2\pi\) < 1.25) with low shear (i.e. a small variation of \(t/2\pi\) across the magnetic surfaces). The major radius of the plasma is 5.5 m, the effective (i.e. averaged) minor radius is 0.55 m, and the magnetic axis is helical.

A main goal of W7-X will be to demonstrate the suitability of optimized stellarators as a fusion power plant. Therefore, apart from proving the properties predicted by the numerical optimization, i.e. confinement in the range of that seen in tokamaks of comparable size, W7-X will explore the question of instabilities under optimized conditions, turbulent transport and steady-state operation close to operational boundaries. W7-X will also develop further the island divertor and will address plasma-wall interaction in long plasma pulses. To allow for steady-state operation (i.e. pulse lengths of 30 minutes), Wn 7-X will have a superconducting magnet system composed of 50 modular coils and 20 planar coils. The latter are intended to explore the plasma under small variations of the numerically optimized magnetic field configuration.

III. COMPONENTS OF W7-X

Fig.1 shows a CAD drawing of W7-X, showing all the important basic components which will be described in the following. According to the five-fold symmetry mentioned above, W7-X is made of 5 identical modules with a flip-symmetry of the two respective half-modules.

Figure 1. CAD drawing of the setup of Wendelstein 7-X
Figure 2. Schematic view of one magnetic module of W7-X, comprised of 2 flip-symmetric half-modules, each containing five non-planar coils (type 1-5), 2 planar coils (type A and B) and one control coil in the divertor.

Figure 3. The first non-planar coil (AAB18, type 3), delivered to IPP by the end of 2004. To the right one can see the interlayer connections which also serve as in- and outlet of the He coolant.

A. Magnet system

The superconducting magnet system of W7-X is composed of 50 non-planar coils (of 5 different types, according to the symmetry described above), 20 planar coils for variation of the magnetic field configuration (2 types), a bus-bar system to connect these coils electrically, a central support structure and a set of support elements fixing the coils to the central ring and supporting them against each other. The total cold mass of this magnet system will be 392 tons. Figure 2 shows a schematic view of the coils of one stellarator module.

1) Magnetic coils

The base element of all the coils is the superconductor which is a cable-in-conduit-conductor, manufactured by a consortium of EAS/OCSI. The cable is fabricated from 243 strands (Cu-stabilized NbTi) which are cabled and then co-extruded into an Al-jacket. This conductor has a void fraction of 37% between the cable and the jacket which is used for the flow of the supercritical He coolant. The qualification of all the production and testing steps required extensive efforts resulting in a delay of the conductor fabrication. As of now, however, almost all the conductor for coil manufacturing has been produced and tested.

The 50 non-planar coils that comprise the centerpiece of the magnet system are manufactured by a German-Italian consortium of Babcock Noell Nuclear and Ansaldo Superconduttori. For each coil 6 lengths of superconductor are wound as a double-layer with 18 turns each, i.e. 108 windings in a coil. This winding pack is then impregnated and is embedded in a cast steel casing made out of two half-rings which are welded together. Very stringent tolerances on the geometric dimensions of the winding packages are needed due to the high accuracy required for the magnetic field. Measurements on the already fabricated winding packages showed an absolute deviation from the CAD model of < 3 mm, corresponding to a deviation from the average shape of less than 2 mm [5]. This leaves a margin for assembly tolerances of about the same order, i.e. 2 mm.

Due to the complicated shape of the casings it turned out that the cast material often had imperfections. Therefore it became necessary to investigate all casings carefully using linear accelerators to search for these imperfections and to repair them to guarantee the stability of the coil casing.

Finally, the casing is covered by Cu stripes that conduct the heat to the stainless steel cooling system welded to these stripes. The six superconductor lengths in one coil are connected in series through low resistance joints which are also used to introduce the liquid He for the cooling of the superconductor. Figure 3 shows the first non-planar coil, AAB18, delivered to Greifswald at the end of 2004.

The development of these coils required more time than anticipated, but now series production has been reached. As of now, 43 out of the 50 winding packs have been built, 27 coils are in different stages of fabrication and seven have been delivered already [6]. Three of these coils have been tested individually at cryogenic temperatures in full-current operation and have proven the expected properties [7]. These cryogenic tests are being performed for all non-planar and planar coils at CEA in Sacly/France as part of the final acceptance test.

The 20 planar coils (supplied by Tesla in the UK) use the same superconductor as the non-planar coils. Their casings, however, are made from two vertical rings and top and bottom plates bolted to them. Recently refined structural calculations of these coils demonstrated the need for a reinforcement of these casings by additional shear pins in the top and bottom plates. This reinforcement is under way and the first final coil will be delivered in October 2005. One other coil (without the reinforcement yet) has successfully completed the cryogenic tests already.

2) Busbar system

To connect the coils with each other (seven groups of 10 identical coils in series) and with the current leads (which connect the busbar system to the power supplies at ambient temperature), a superconducting busbar system is required which is being designed and manufactured by the research centre Jülich (FZJ, Germany) [8]. The same conductor is used as for the coils and the routing is done in a bifilar way to reduce error field from the busbar. The design of the busbar system has been finished and manufacturing will start soon.

3) Power supplies and current leads

The seven groups of superconducting coils mentioned above are powered by seven power supplies manufactured by the Swiss company ABB. Each power supply delivers a direct current of up to 20 kA at a voltage of up to 30 V. This system
The output currents can be stabilized to the required accuracy of $2 \times 10^{-3}$.

The connection between the power supply lines outside the cryostat (i.e. at ambient temperature) and the busbar system inside the cryostat (i.e. at about 4 K during operation) requires seven current leads that bridge the temperature transition. A contract for the development of these current leads which have to be installed in the bottom of the cryostat, has recently been started with FZK in Karlsruhe.

4) Support structure

The 50 non-planar coils will all be fixed to a central support structure, which is manufactured by Equipos Nucleares S. A. in Spain. This ring is composed of 10 identical, welded, segments which are bolted together to form a pentagon of 5 modules. As the coils have to be kept in their precise position, also during cool down and operation, the half-modules of this central ring have to be machined to a high accuracy of a few tenth of a millimeter. The positioning of the 5 modules of the structure against each other can finally be adjusted by shim plates during assembly. The manufacturing of this component has experienced several delays as the continuous refinement of structural calculations [9] resulted in different modifications to the detailed design of the structure and also technical problems with surface cracks in the cast extensions required additional R&D. The first segment of the support ring (see Fig. 4) is scheduled for delivery early in 2006.

5) Support elements

Each coil is fixed to the ring by 2 extensions, so called Central Support Element (CSE), which have to take up the magnetic forces (up to 4 MN) and bending moments (up to 350 MNmm) [10]. A bolted solution using long and slender Inconel bolts (which better absorb deformations) and sleeves to limit the loss of pre-load during cooling down to 4K has been developed to keep the coils firmly in place.

Also in toroidal direction, the non-planar coils have to be supported against each other with a system that can take up the forces and moments and keep the positions of the coils to a high accuracy. Therefore, on the inner side of the coil set, where the coils are very close to each other, the so-called Narrow Support Elements (NSE, see [11]) and on the outboard side so-called Lateral Support Elements (LSE) are foreseen [12]. These LSE will be a rigid connection made of half-boxes which are inserted between the coils and then are welded to the coils and to each other. The crucial issue with this design is the proper control of welding shrinkage and distortion which is essential to comply with the magnet system assembly tolerances. An extensive test programme has been carried out and is still going on to identify the best LSE boxes layout and welding procedures in order to ensure that the shrinkage is as repeatable and as parallel as possible [12].

The situation is different for the NSE because on the inboard side of the coils accessibility restrictions do not allow any welded or bolted solution. Based on refined FEM calculations which revealed that contact forces up to 1.5 MN and sliding distances of up to 5 mm with a tilting up to 1 degree have to be expected during magnet energization, a sliding pad solution has been selected. After an extensive test programme, Al-bronze with an MoS$_2$ coating has been selected as the material for thick, low friction pads which are fixed in a pad holder to one coil, sliding on the support block of the other coil. To validate the basic design and to identify the best pad coating, a wide test programme has been undertaken, including full scale friction tests at room temperature and cryo-vacuum tests at 77 K to test the full scale mock-ups in a more representative environment.

This test programme is now coming to an successful end. The detail design of these Narrow Supports required also a redesign of the Narrow Support blocks on all non-planar coils as late as summer 2004, resulting in a further delay of coil fabrication.

A design similar to the one for the NSE will be used for the so-called Planar Supports which support the planar coils against the non-planar coils.

B. Cryostat

The cryostat, providing the thermal insulation of the cold magnet system described before, consists of the plasma vessel, the outer vessel, the ports and the thermal insulation of these components towards the cold mass.

1) Vacuum vessel

The vacuum vessel is manufactured by the German company Deggendorfer Werft und Eisenbau (MAN DWE) [13]. A major issue of the vacuum vessel design was the optimization of its shape to allow maximum space for the plasma and to simultaneously keep sufficient clearance to the coils. These requirements result in a tolerance of only ±3mm for the shape of the plasma vessel. The full plasma vessel is made up from 200 rings (each covering 1.8° in toroidal direction) that are connected by welding. Each ring is made of four segments that are exactly bent to the exact shape and 20 rings form one half-module. Cooling pipes on the outer side of this vessel allow a bake-out at 150° C and temperature control during plasma operation.
and dimensions (up to 40 x 100 cm² rectangular ports) to allow flanges. This first module will be delivered at the end of 2005.

3) Ports

W7-X will be equipped with 299 ports of different shape and dimensions (up to 40 x 100 cm² rectangular ports) to allow access from the outside to the plasma vessel [13]. 160 of these ports will be used for plasma diagnostics, 19 for heating systems, 20 for pumping the vacuum vessel and 100 for supply of in-vessel components. The Swiss company Romabau Gerinox delivered already 226 of these ports, the remaining ports are scheduled to be delivered in spring of 2006.

4) Thermal insulation

Efficient cooling of the superconducting coils requires very effective reduction of heat conduction as well as shielding of radiation from the room temperature components of the cryostat.

The thermal insulation of W7-X (also manufactured and assembled by MAN DWE) is composed of two components, a multi-layer insulation of aluminized Kapton-foils (20 layers) and a rigid thermal shield. As the space limitations for this insulation (between the vacuum vessel and the non-planar coils) require again a tolerance of ± 2 mm, the original concept of a metallic shield had to be given up. Instead, the thermal shield is now fabricated from glass-fibre panels with embedded Cu-meshes to improve heat transport within the panel. Cooling pipes on the outboard side of the panels are connected to the Cu meshes through Cu-braids. For each half-module of the vacuum vessel, eight panels of the shield with attached multi-layer insulation are fabricated. They are assembled on the plasma vessel in parallel with the threading of the coils, i.e. at present four such panels have been mounted on the first half-module, see Fig. 5.

C. In-vessel components

At the plasma edge, i.e. outside the closed flux surfaces, the magnetic configuration of W7-X forms a m=5 island structure to be used as an island divertor to control the power and particle exhaust from W7-X [14]. According to the five-fold symmetry of W7-X, also the divertor will have such a structure, i.e. it will be composed of 10 units, five on top and five on the bottom. The full system of the in-vessel components includes several plasma-facing elements (the target plates, the baffle plates and a wall protection on the inner surface of the plasma vessel, as well as cryo pumps and correction coils to modify the extent and location of the islands on the target plates. This system has been designed for steady-state operation at the full ECRH-heating power of 10 MW and for 10 s pulses of 15 MW NBI heating power.

With regard to the plasma-facing components, three different areas have to be distinguished which require also different technical solutions. The divertor target (with a horizontal and a smaller vertical target plate) will experience high power fluxes of up to 10 MW/m². The baffle, that shields the neutrals in the target chamber versus the main plasma chamber, experiences lower stationary power fluxes of only up to 0.5 MW/m². The wall protection, covering the rest of the plasma vessel surface, is subjected to neutral particles and plasma radiation and is designed for power fluxes of 0.2 MW/m².

1) Target plates

Fig. 6 shows a CAD model of one divertor target module with a total plasma facing surface of about 2 m² [15]. To achieve a homogenous heat distribution on the target plates, their shape has to follow closely the 3D shape of the plasma. This is achieved by dividing the target plates with a total surface of 19 m² into 100 target modules with a total of 890 tiles, each of them covering a toroidal width of up to 55 mm. The final surface of the target modules is then machined carefully to achieve smooth surfaces without any leading edges that would experience extensive heat loads.

Numerical modeling of the expected heat load revealed a rather localized power distribution which will also vary for different magnetic equilibria. Therefore, while most part of the target can withstand heat loads of up to 10 MW/m², the middle part of the horizontal target plate has to withstand only power loads up to 1 MW/m². For this part, the same technology is used as for the baffle plates (see below). These sections of the ten divertor modules with a total area of about 5.6 m² will be composed of 20 target modules with a total of 240 target elements.

For the high-heat-load target area, however, 6 mm thick carbon-fibre-composite tiles (NB31 from Sncema, France) are used which are bonded to a CuCrZr heat sink that is also water-cooled, but equipped with swirl-tubes to enhance heat exchange. These target elements will be manufactured by Plansee in Austria. The first series CFC elements have been produced, but show a reduced tensile strength in one direction.
island structure and also the sweep the island structure over the plasma edge, i.e. to optimize the position and extent of the target modules. These coils will be used to correct small field errors at the target plates.

Presently it is investigated by Plansee whether they can be used nevertheless. To save on capital costs, completion of the target modules, i.e. the integration of target elements into modules fixed on a base structure, as well as the testing of these modules will be done within IPP.

2) Baffle plates

The baffle plates at the transition from the divertor region to the main plasma chamber are intended to reduce the backflow of neutrals from the divertor region to the plasma main chamber and to enhance the neutral density in the divertor and pumping region.

As these plates see a much lower power flux density, they can be made in a somewhat simpler technology, i.e. from 20 mm thick grain graphite elements clamped to a water-cooled CuCrZr alloy heat sink. They cover an area of about 30 m² and are fabricated in 170 baffle plates with a total of 2900 baffle elements. The baffle elements will be fabricated in the workshops of IPP Garching.

3) Wall protection

The plasma vessel has an inner surface of about 130 m², only a small part of which is covered by the in-vessel components described before. For coverage of the remaining wall, two different techniques will be used.

In areas where the plasma is close to the wall, i.e. mostly on the inner side of the torus and between toroidally adjacent divertor segments, the heat load may be somewhat higher. In these areas with a total surface of about 30 m², Carbon tiles clamped to a water-cooled structure, with the same design as for the baffles, will be applied. On the remaining surface of about 65 m², mostly on the outboard side, stainless steel panels with integrated water-cooling will be used. These panels will be coated with B₄C to improve the plasma-wall-interaction. Prototypes of such panels have been produced with the required accuracy by MAN DWE who now will manufacture these panels.

4) Control coils

Ten control coils will be installed behind the baffle plates. These coils will be used to correct small field errors at the plasma edge, i.e. to optimize the position and extent of the island structure and also the sweep the island structure over the target plates to distribute the power load to the target plate dynamically.

These coils are made of a hollow Cu conductor and are cooled by water. They are manufactured by BNN in Germany and the first coil is to be delivered in October 2005.

Each of these coils will be supplied by its own power supply with a DC current of 3 kA at voltage up to 30 V that can be modulated at frequencies up to 20 Hz. These power supplies have already been delivered by the Spanish company JEMA, the final acceptance is under way.

5) Vacuum system

The main vacuum system, used to evacuate the plasma vessel and to exhaust the neutrals from the divertor region during plasma operation, will use turbomolecular pumps with roots and rotary pumps as forepumps. The system is foreseen to provide a pumping capacity of 42 m³/s. Positioning and shielding of the turbomolecular pumps has to consider the sensitivity of the rotors to magnetic fields.

To enhance the pumping capability in the divertor, behind each of the baffle modules a cryo pump will be installed. These cryo pumps, intended to provide an additional pumping capacity of about 75 m³/s in the divertor chamber, are manufactured in the Garching workshops of IPP.

IV. W7-X ASSEMBLY

Assembly of Wendelstein 7-X is a very complicated process that requires a very high accuracy in all assembly steps in order to guarantee the tight tolerances required for the magnetic field deviations mentioned above. The process itself is divided in 5 major steps [16] to be described below. For these very complex steps many technologies have been developed and qualified, assembly steps have been trained to train the personnel but also to commission and to optimize the newly developed tools [17]. Threading of the coils has been simulated with interactive CAD-models to check early for possible collisions.

As the first step of assembly, 5 non-planar coils and 2 planar coils are threaded over one half-module of the plasma vessel with the thermal insulation, NSE and LSE being mounted in parallel. As the space between the vessel (and the thermal shield) and the non-planar coils is very limited, special handling tools have been developed that allow to move and rotate the coils very precisely. A second tool has been developed to handle the planar coils. At the end, when all seven coils have been aligned precisely, the non-planar coils are fixed to one half-module of the central support ring with the CSE. This process is done in two assembly stands of type I in parallel for the two half-modules of one magnet module.

In the second step, these half-modules are connected with each other in assembly stand II, i.e. the central support ring half-modules are bolted together and the vacuum vessel is welded. Then the busbar system is assembled, including the 182 joints between single conductor pieces which have to be installed and leak tested.
The third step foresees that the completed magnet module is transported into assembly stand III in the torus hall where it is placed in the lower half shell of the outer vessel which by then has already been equipped with its thermal insulation.

This assembly is then transported to its final position on the machine base where the insulated upper half-shell is put on top and the outer vessel module is closed. Then, about 60 ports and some base components of the in-vessel components are installed.

Once, all five modules are in their position, the final step can be performed. The position of each magnet module can be adjusted within ±5 mm in a final optimization step. This optimization will be based on the exact as-built data of all coils and on their exact positions within a magnet module. Shim plates will be used to close the small gaps that were left between the central support modules. Then the plasma and the outer vessel modules are welded together to close the torus. Some remaining ports, i.e. those at the border between modules are assembled and the thermal insulation is completed.

Because already after step 4 the modules are almost in their final position on the machine base, assembly of periphery systems (diagnostic, heating systems, water, cryo and electrical supply lines) can start then. The final assembly of the in-vessel components, however, will be done only after closing the torus. The reason for this being that only after welding of the plasma vessel segments the exact positions of the target plate supports are fixed and only then the exact target plate position can be adjusted.

V. Schedule

Because of delays in the production of the coils and in the development of the support elements, but also due to the complexity of the assembly, completion of the W7-X construction got further delayed. Assembly of the first non-planar coil started in April 2005 (see Fig. 8), as of now two non-planar coils have been assembled. Presently assembly of the NSI is being qualified and these pads will finally be installed in near time. As of now, the progress of assembly is still limited by the availability of coils, but as the delivery situation improved well over the last half year, and now the cold tests in Saclay run routinely, this will change soon.

But still, assembly of the torus will not be finished before mid of 2010, and assembly of the in-vessel-components will take until summer 2011, when commissioning of W7-X can start. Start of plasma operation is therefore scheduled for the summer of 2012.

REFERENCES