Status of Wendelstein 7-X Construction

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Abstract

Wendelstein 7-X (W7-X) represents the continuation of fusion experiments of the stellarator type at the Max-Planck Institute for Plasma Physics. The aim of W7-X is to demonstrate the suitability for a fusion reactor of this alternative type of magnetically confined plasma experiment. W7-X is being built at Greifswald in the northeast of Germany. The size of device (725 t, height of 5 m, diameter 16 m) and the superconductive magnet system distinguish W7-X from earlier stellarators at the Max-Planck Institute. The paper provides a summary of the status of the main components, the mastering of the technical challenges during component acceptance testing and during machine assembly. Latest results of the assembly works are especially highlighted. The scope of the construction of Wendelstein 7-X was modified and additional acceleration measures were implemented to mitigate risks and delays. Some aspects of these changes are explained in this paper.

Keywords: Wendelstein 7-X, W7-X, fusion, stellarator, superconducting magnet

1 Introduction

W7-X is designed for steady state operation at full heating power, but limited to 30 minutes due to the capacity of the external heat rejection system. The experimental verification of an improved magnetic confinement of the optimised stellarator, the continuation of the island divertor development and the examination of the plasma-wall interaction are essential physics aims [1]. A major technical aim of the Wendelstein 7-X experiment is the demonstration of the constructability of this superconducting and modular-built machine with optimised stellarator geometry. The basic machine (Fig. 1) comprises the superconducting magnet system (coils and support structure), the cryostat (vessels and ports) which envelops the magnet system, the plasma facing components, located inside the plasma vessel, and the associated services like power supplies, vacuum systems, helium coolant system, water cooling and heating circuits etc. Large single components are: 50 non-planar and 20 planar superconducting coils (about 3m diameter each); the central support structure which supports the 70 coils; the plasma vessel, the outer vessel and 254 ports which interconnect both vessels to provide access into the plasma vessel. The machine is made up of 5 modules (five-fold symmetry). Every module weights about 150 tons. Each module is subdivided into two flip-symmetric half-modules. The assembly of the modules is made at different assembly stages, as much as practical in parallel to shorten the assembly schedule as much as possible.

The design and manufacturing of the W7-X components have progressed well within the last years. Difficulties with the production of some main components like the coils were overcome successfully.

The design capacities in the project were increased considerably as well as the capability to carry out collision checking (back office). Complex 3D collision checks are an integral part of all design work on components. The additional as-built control (reverse engineering) of the delivered and mounted components is very important to avoid any clashes between components during operation [2]. The extent of digital scanning of components required for collision checks has also been expanded considerably. The analysis and structural calculations for the assemblies of the W7-X have been substantially further developed. Comprehensive models for the FE-analysis have been generated [4].

Apart from the basic machine and the supply systems (cooling water, electricity, helium, vacuum, gas), several plasma heating systems (ECRH, NBI, ICRH), the start-up diagnostics for the experiment operation, as well as a data acquisition and data processing system are part of the basic equipment of the entire facility [5], [6], [7], [8], [37]. The start-up diagnostics will be improved and completed in the course of the experiment operation. No detailed reference is made to these components and systems in the paper.

2 Basic device components

2.1 Magnet system

2.1.1 Coils and coil testing

The manufacturing of 50 non-planar and 20 planar coils has finished. The problems with the strength of the electrical insulation have been fixed successfully by repair measures. 20 coils still must pass the acceptance test in the CEA test facility. The operation of the test facility has stabilised in the past months. With the present test rate the remaining coils can now be tested and delivered on time for assembly. It is expected that quality deviations found during these tests are not critical and can be accepted without repair. More details are summarised in [9].

2.1.2 Bus-bar system

All bus-bars for the first two modules have been manufactured and delivered to IPP. The first 24 bus-bars are already assembled in the first module. About 100 mechanical supports for the first module have been delivered and assembled. The construction works for the following modules are continued. More manufacturing capacity for supports and clamps must be bound in the future, to keep these components away from the critical project path. The production and delivery of the superconductor joint components run as planned. These joints are used to connect the bus-bars with the coil terminations. More details about design, analysis and manufacturing of the bus-bar system are described in [10] and in chapter 3.2.2 of that status report.

2.1.3 Current leads

7 pairs of current leads connect the power supplies with the 7 coil groups of the superconducting magnet system of W7-X. The nominal current amounts to 18 kA. Current leads are installed with the cold end at the top. They contain high temperature superconductors, heat exchangers at the 4 K level, a separate vacuum supply, high-voltage insulation up to 13 kV as well as temperature and quench detection sensors. Current leads are about 2.5 m long and weigh about 300 kg each. They are connected to the outer vessel via a pivot system and to the central ring of the magnet system via flexible joints. More details are explained in [11]. Current leads are developed, designed and manufactured by Forschungszentrum Karlsruhe. Prior to series production a prototype will be produced and tested comprehensively.

2.1.4 Coil supports structure and magnetic supporting structures (cry legs)

4 segments (half-modules) of the central support structure have been delivered by ENSA (Spain). They have already been attached to the coils.

The manufacturing of supporting structures for the magnet system has started. Altogether 10 cryo supports carry the complete weight of 425 tons. They are supported on sliding bearings at ambient temperature to allow for thermal shrinkage during cool down to 4 K. Integrated in the design of the cryo supports is a thermal barrier that separates the 4 K parts from the ambient temperature parts. The thermal barrier, a G10 tube and the associated connections to the steel parts of the supports have to withstand high forces and moments. A comprehensive test- and qualification program was successfully carried out to assure the mechanical and thermal requirements [12], [13].

2.1.5 Central supports and inter-coil supports

Central supports connect each coil at two flanges with the central support structure. The single connection consists of a highly and very precisely tensioned bolt array and welded fitting wedges [14], [15]. The cross section of that connection amounts to about 180 by 180 mm.

The inter-coil supports comprise sliding narrow support elements (NSE), sliding contact elements (CE) and welded lateral support elements (LSE) between adjacent non-planar coils as well as sliding planar support elements (PSE) between non-planar and planar coils. The sliding support consists of a slightly spherical pad located between two counter-sides at the coil casings. This design works as composite glide and tilt bearing with a very high surface pressure. For the improvement on the gliding features the affected areas are coated with MoS_2. Details of the construction and dimensioning of these supports are explained in [16] and [3]. The installation of the supports must be carried to a very high accuracy. That requires special assembly proceedings (see chapter 3.2). Support elements weigh between few kg and 45 kg. All these elements are already installed in the first two modules. The manufacturing and adjustment on-site of these parts is continued and is further optimised.

2.2 Cryostat

2.2.1 Plasma vessel and outer vessel

The preparation and assembly of the plasma vessel modules including associated cooling pipes, thermal insulation, sensors and cables proceeds as planned. Two modules are complete; the third module is at present prepared. The first three plasma vessel supports were positioned and welded in the lower shell of the first outer vessel module. The achieved accuracy lies within the expected range of about 2 mm. More details are described in chapter 3.3.1.

The first module of the outer vessel (bottom shell and upper shell) was delivered. The next two modules passed successfully the acceptance test at the manufacturer. The fourth module is prepared for the acceptance test. Final welding is carried out at the fifth module. Manufacturing and delivery of the vessels occurs according to the planning [17].

2.2.2 Ports

All ports have been delivered. 254 ports will be installed in W7-X. Ports weigh between a few 100 kg and about 1000 kg. They range from 1.5 m up to 2.5 m long with cross sections varying from circular of 100 mm in diameter to rectangular with dimensions of 400 by 1000 mm^2. First preparation work (incoming inspection, metrology survey) of ports is carried out (Fig. 2). To extend the clearance to neighbouring components in the later operation, the cooling pipe routing is adapted on some ports. In addition some special ports are modified to guarantee they can be installed within the available space. Some further details of these adaptations and of the assembly technology are given in the chapter 3.3.5.

2.2.3 Thermal insulation

The thermal insulation of the first module and of the two following half-modules of the plasma vessel is complete including the brackets, domes, cryo shield and helium pipes. This work continues and is further optimised.

For the outer vessel and the ports the design and manufacturing of the insulation for the first module is ongoing. This design is very complex since the installation space is very restricted in the cryostat [18]. More design and manufacturing capacity is foreseen in the future to keep the delivery and assembly of the thermal insulation away from the critical project path.

2.2.4 Helium piping and cryo cooling of components

The design of pipe segments and mechanical supports for the first module is complete to a large extent. The manufacturing is ongoing. Pipes vary in diameter from 10 to 50 mm at lengths up to 4 m. About 300 individually 3D-bent pipes form the entire pipe system of one module. The geometrical accuracy of manufacturing and assembly must lie within few millimetres. In each module the pipes are connected by about 500 welds which are mainly made with standard orbital welding technique. All welds are inspected visually and by helium leak-testing. Delays can be avoided in future only by the strong acceleration of manufacturing. More details about the helium piping system are presented in [19] and in chapter 3.2.3 of this paper.

2.3 Helium refrigeration plant

The helium supply system is almost complete. It can be operated in a very complex and variable way [20]. All main components of the helium plant have been installed. Commissioning tests of the entire facility are running as planned.

2.4 In-vessel components

The in-vessel components comprise wall panels and heat shields for the wall protection, the divertor with baffles and horizontal and vertical closures, control coils and cryo pumps. A complex cooling pipe system, sensors, cables and some embedded diagnostics complement the system. For the in-vessel components a functional specification which corresponds to the project plan updated in 2007 was made. This plan stipulates that as many components as possible become installed for the first operating phase within the available time windows. Further design details are described in [21].

Target elements for the High Heat Flux (HHF) divertor are tested in the IPP test facility GLADIS. One sample element was successfully tested at $10MW/m^2$ with 8500 load cycles [23]. Target elements are made of carbon-fibre composite (CFC) tiles connected with a copper chromium zirconium (CuCrZ) base structure. Inner cooling channels enable active water cooling. The target elements are made by Plansee.

The conceptual work for the test divertor unit (TDU) has been started [22]. This comprises design, manufacturing and assembly. Work on the heat shields, baffle modules and wall panels are proceeding as planned. Some smaller modifications were implemented into the existing design because some ports have been omitted and therefore the associated openings in some components needed to be closed. Design and manufacturing of the water cooling pipe-system will be accelerated to minimise possible schedule risks. All control coils have been delivered to IPP.

2.5 Power supply and protection for the magnet system

The power supplies for the 7 coil groups of the magnet system are completely installed. Their trial operation is in preparation. A prototype of the quench detection control rack with 72 individual detection units was successfully developed and built by FZ Karlsruhe. It is now comprehensively tested. The data acquisition system was also developed and examined. The preparation for the procurement of the components for the serial production has started. The design works at the super ordinate control system are running as planned [24].

3 W7-X Assembly

The assembly process is organised such that it corresponds to the modular construction of the W7-X. To a large extent 5 equal modules form the base machine. Each module is split into two flip-symmetric half-modules. The individual half-modules of magnets and support ring are assembled, then two half-modules to form a module. In the final assembly the 5 magnet/ring modules are assembled into outer vessel shells and the accompanying ports are installed. This provides 5 single machine modules which are finally connected to each other. A comprehensive preparation phase for all components is needed before they can be assembled. All assembly work has been distributed logistically on several mounting stands (MST). Therefore some work can be made in parallel in order to save time. The pre-assembly of the magnet half-modules is carried out at MST Ia and Ib (coils, plasma vessel sectors, support structures). The module assembly is continued in MST II and III (bus-bar system, helium pipe system). The final assembly of the W7-X modules takes place at MST IVa and IV (outer vessels) as well as MST V (ports). The machine base which carries the complete W7-X is integrated into the mounting stands IV and V. All mounting stands are temporary and are removed after completion of the assembly. More details about the assembly technology are presented in [25], [26]. Special problems with clearances in the assembly arise from the very narrow installation space in which the components must be installed. This requires the massive use of 3D measurement techniques like laser trackers, photogrammetry and laser scanning [27]. The welding engineering is also demanding ranging from the aluminium jacket of the superconductor to connections of the steel structure components with up to 25 mm of welded seam depth with tolerances of less than one millimetre being adhered to. Special welding procedures were developed for this with controlled heat guidance. Welded joints at pipes and vessels are leak-tested. In cases of very poor accessibility special procedures and devices were developed for the introduction of the test gas (helium).

3.1 Component preparation

Work on coils, the segments of the support structure, the plasma vessels the bus-bars and helium pipes run as planned. Ways are investigated to reduce the scope of additional preparation work on these components (e. g. at the adjustment of coil terminals).

With respect to further main components like outer vessels and ports this work has just started. Civil works in an external hall are continued to get additional space (about 3000 m^2) for the preparation of outer vessel shells. More details are given in chapter 3.3.1.

3.2 Pre-assembly

3.2.1 Mechanical pre-assembly

Works on mounting stands Ia and Ib were continued as planned and run well. 4 out of 10 half modules are complete. The next two are being assembled at present. Possibilities were analysed and will be implemented to accelerate this series assembly work. A complex technology for the assembly of the central supports and the inter-coil structure (chapter 2.1.5) was developed and implemented successfully. The technology entails the measurement of 14 shims and 50 wedges this is done by spring pins for the shims and harden able plastic compound for the wedges. After processing of the data the wedges are fitted and welded under strict positional control. Welding the lateral supports is also carried out via a specific control of the weld shrinkage.

3.2.2 Installation of bus-bars

The mechanical work on the magnet system and plasma vessel of the first module is finished (Fig. 3). The coil services are being installed at present, i.e. superconducting bus-bar system, the helium-pipe system and the sensor-instrumentation. First works for the installation of the bus-bar system on this module were carried out. The bus-bar installation is divided into three stages: The bus bar support brackets (more than 100 in total) are accurately positioned and fixed [10]. In the second stage 24 pre-fabricated bus-bars (lengths between about 4 m and 14 m) are threaded and stacked in the support bearings and clamped together (Fig. 4). To balance the weight of the bus-bar during the tricky threading operation, it is suspended from balloons filled with helium [10]. The superconductor joints are installed in the third stage to connect bus-bar ends and coil terminals electrically and hydraulically.

3.2.3 Installation of helium piping

The installation of the helium-pipe system has turned out to be as demanding as the bus-bar system. Batches of pipes known as “lots” are positioned above and below the bus-bar system. A lot comprises up to 50 single pipes (∅ 10 to 50 mm; lengths about 2 m) which are precisely pre-bent (+/- 2 mm) by the manufacturer according to the 3D CAD model. The pipes are fastened to the coils and structural elements.

G10 spacers in the support bearings prevent inadmissible heat conduction between neighbouring pipes at different temperature levels (inlets, outlets).

3.2.4 Installation of module instrumentation

The module instrumentation comprises sensors and cables on the magnet module, on the cryo side of the plasma vessel and on the cryo shields that cover the vessel walls within the cryostat. This is mainly for the operation of the basic machine (magnet system and cryostat). The instrumentation of the in vessel components (KiP) and the experiment diagnostics is separately carried out in a later assembly stage. Rogowski coils and saddle coils are installed and cabled in conjunction with the module instrumentation. The cabling system for the module instrumentation consists of low voltage cables for strain gauges (about 60) and thermal sensors (about 140) and high voltage cables (about 40) for the quench detection system of coils, bus-bars and current feed throughs. Sensors are distributed along the entire module. Low voltage cables and high voltage cables are separated from each other. This minimises mutual interferences of sensor signals.

3.3 Final assembly

3.3.1 Preparation of outer vessel shells

The final assembly of the first module has not started but the preparation work is already underway. The first module of the outer vessel was delivered and stored in a separate preparation area of about 3000 m^2. This module is divided horizontally into two shells, a bottom and an upper one. A shell weighs about 14 tons and is rather flexible due to many openings. At the inside of a shell the thermal insulation and the thermal shield (TI) will be fastened. To not damage the TI during the handling and assembly of the outer vessel shells they must be stiffened and reinforced. The design of the TI requires that any deformation at the shells is limited to less than 5 mm. The stiffening system required (TMV) consists of a steel framework (Fig. 5). Tensioning pieces hold the shell within the framework and enable the adjustment of the geometrical contour of the shell. About 20 reference points and laser tracker measurements are used to control the adjustment. The shell remains in its TMV until both shells have been welded together.

3.3.2 Installation of plasma vessel supports

Another task in the preparation of outer vessel shells comprises the positioning and welding of plasma vessel supports (PGA). Three supports are assembled into every bottom shell [31]. They carry a module (a fifth) of the entire plasma vessel. 5 adjustable bearings will hold the vessel in horizontal direction. This enables a controlled movement of the vessel during baking to 150 °C for example. In the first bottom shell the three supports were successfully installed. For the achievement of the specified geometrical accuracy (less than +/- 2 mm at the top) a welding procedure with controlled shrinkage behaviour was essential. The welding experiences for the structural components in the pre-assembly could be applied here (see chapter 3.2.1).

3.3.3 Installation of thermal insulation

The main task during the outer vessel preparation comprises the installation of the thermal insulation including the thermal shield. These works will be carried out by the supplier of the thermal insulation, MAN DWE GmbH. It is planned to start these works in autumn this year. These works will last more than 6 months per shell, at least for the first shells. This duration exceeds the time allocation in the schedule and makes it necessary that two shells are processed parallel in order to be available for the final assembly on time. This requires additional space and equipment, which is being provided at present.

3.3.4 Technology developments for the final assembly

The technological preparation for the final assembly is ongoing. For the assembly of the individual vessel modules most of the required procedures and equipment have already been obtained. The handling and positioning of the 100 tons magnet modules and the proper functioning of the associated equipment was successfully tested with a 1:1 mock up. The achieved position and contour accuracy was better than 1.5 mm which is much better than originally estimated. During these tests valuable information was gained about improvements for the cranes.

3.3.5 Assembly of ports

For the assembly of ports the required equipment is manufactured in the industry at present. A port-assembly bridge spans three sides of the module. It takes a port assembly ramp, which enables the precise alignment of ports in all 6 degrees of freedom. To be able to install ports also from the bottom side, a second port ramp is operated from the floor. In the standard procedure a port is simply fitted into the existing “as built” holes in the “as positioned” vessels. No extra alignment to the theoretical CAD co-ordinates is made. But the “as assembled” position of the port is measured and documented. The detailed standard assembly procedure was already described in [25], [26]. The port ramps and the bridge will be available by the beginning of 2009.

For almost all ports this method will be sufficient, but in some special cases it can become necessary to install the ports at accurately pre-defined positions instead of fitting them simply into existing vessel holes. The cause for it can be, for example, tolerance deviations or a very restricted installation space. These will be treated as individual cases. For the neutral beam injection port (NBI port) such an alternative installation procedure was developed [32].

Welding the ports to the vessels is a special challenge since vessels have a poor stability due to many openings. Standard welding procedures can not assure that the welding shrinkage does not deform the vessel contour by more than a few millimetres. Special narrow gap procedures are tested at present. Per module a welded seam length of about 150 metres must be made. The weld seam thickness is between 8 and 12 mm. The welding sequence and proper temperature control are required to avoid inadmissible deformations of the vessel. Welders must be changed regularly due to the typical work height in the plasma vessel of only 1.5 m. Also this well isolated vessel must be cooled during welding. Suitable methods for the leak test and for the placement of the shielding gas to the rear side of the welded seams was recently tested successfully [33].

The number of ports to be installed was reduced to 254 in 2007 in conjunction with the revision of the entire W7-X project plan. This saves assembly time and reduces the complexity of the assembly and hence the risk. First practical results of the port assembly will be available in the middle of next year. The preparation of ports is organised as a separate work package in parallel to the main assembly process in a separate preparation hall and has started. After the port installation some supplementary work is done including the installation of feedthroughs for the instrumentation cabling [34] and for the cooling circuits of vessels and ports.

3.3.6 Connection of neighbouring modules (module separation plane)

With the installation of the ports a single module of the W7-X is completed with the exception of the plasma facing components. Once three modules have been completed the connection of neighbouring modules (module separation plane) can start at the earliest in the middle of 2011. The concept for the connection of neighbouring magnet modules (shim plates, bolts, fitting elements) was already worked out. This work is similar to that successfully applied in the pre-assembly. Tools and work procedures have to be qualified and described in detail. These tasks are assessed to be not critical at the moment.

In contrast to this, the work to connect neighbouring vessel modules is challenging. Splice plates are machined to size and shape, precisely positioned in the gap between the modules and welded. On the cryostat side, the thermal insulation must be completed. Both work packages are carried out by the supplier of the vessels however the engineering for it and the direct work must be integrated into the IPP work flow. The wall thickness of the plasma vessel is 17 mm and of the outer vessel 25 mm. Welds of the plasma vessel can only be made from the inside whereas the outer vessel is welded from the outside. In addition some ports are directly located in the splice plate area. A detailed strategy was worked out to minimise the deformation due to the weld shrinkage [35]. After the welding of the vessel modules the standard procedure (bridge and ramps) will be used to install the remaining ports in that area. For those ports blocked by the temporary supports a strategy is in preparation to mitigate the time delay. Other assembly work at the module separation plane including the connection of bus-bars, helium pipes or instrumentation cables has still to be worked out. Another main work package will be the installation of the 7 pairs of the current leads which takes place after all 5 modules are in place. When all 5 modules have been connected the base machine of W7-X is complete except for the machine periphery and the in-vessel components.

3.4 Installation of the machine periphery

The machine periphery comprises the supply systems for cooling water (for vessels, ports and plasma facing components), for gas, for the electrical power as well as the instrumentation cabling inside the experimental hall and the set-up of the experimental platform in that hall. The installation of the vacuum systems is separately carried out but organised in conjunction with the works at the periphery. The installation of the piping for the helium supply in the experiment hall is organised similarly. The first stages of construction for the cooling water supply and for the power supply are already carried out. The conception and construction work as well as layout planning are going on for the supply systems according to the updated project plan.

3.5 Assembly of in-vessel components

The assembly of in-vessel components is made in parallel to the assembly of the plasma vessel from the initial preparation of plasma vessel sectors up to the final completion in 2014 (Fig. 6). Due to the various assembly steps, including welding, it is likely the plasma vessel will distort over this time. Only those components can therefore be installed before the plasma vessel is closed, which can be adjusted later. The geometrically most sensitive components like the divertor can only be installed when all welding on the plasma vessel has been completed. The components are described in detail in [21]. The status of the development of the assembly technology, the assembly sequence and the essential challenges of these tasks have recently been summarised in [36].

In the present planning the assembly of the in-vessel components is divided into four steps. The first step covers the assembly of brackets, support bearings and welded bolts by which the components are fastened later. As a minimum the cooling water pipe work for the components should be installed or pre-assembled for the first operating phase. Some of this work was already started in the first two modules.

In the second step cooling panels, heat shields, control coils, cooling pipes and instrumentation cables and some embedded diagnostics are installed after the installation of ports. Parts of the adjustable support structure for the divertor are also installed. For the work on the module separation plane, i. e. the connection of two neighbouring modules, up to 2/3 of the surface must be kept free in the plasma vessel. This is necessary to avoid damage and pollution to components already installed but also to provide sufficient space for the welding and adjustment work. This prevents most of the planned step two works. The third step continues the work of the second step but in the area of the module separation plane. Due to the problems identified here the relevant planning is being revised.

The installation of the geometrically sensitive divertor with its horizontal and vertical closures is part of the forth step. This work is done at the end of the assembly when the plasma vessel is geometrically stable. This work package lies on the critical project path. The pipe work will be delivered in pre assembled and tested circuits to reduce the amount of in vessel welding and testing. In total about 2000 welds have to be made.

3.6 Assembly of heating systems and experiment diagnostics

These works are separately carried out but organised in conjunction with the general assembly works. Assistance and resources for these works like metrology, leak testing, welding technique and other services are considered in the global assembly planning.

3.7 Assembly planning, work preparation and organisation

The construction of W7-X requires comprehensive planning and work preparation. Qualified procedures are available for the planning and preparation of the assembly work. Basis for the planning are detailed work descriptions and inspection instructions of single assembly steps, e. g. threading of a coil around the plasma vessel. Work descriptions are issued by the responsible engineer for the assembly step. Work instructions are based on qualifications i. e. simulations and tests. Besides the detailed description of the work steps, the instruction contains part lists, assembly drawings, safety advices and instructions on how to use the special assembly equipment. These documents are compiled in a quality assurance and assembly plan (QAAP). This plan is the guiding document for the works on-site. All remarks, deviations and releases of steps are documented in this document. All QAAPs are archived. Experience gained is incorporated for the next module. At present more than 150 QAAPs are issued. In case of quality deviations, the affected working step is stopped and a quarantining card is issued. For major deviations a formal non conformance procedure is started in addition and the associated document is circulated within the project for comments and decisions. The work is continued after the correction and repair measures have been documented and released. In case of urgent decisions a configuration control board (CCB) decides immediately the correction and repair measures.

The time planning for assembly and the allotment of the required resources (equipment, personnel, extended working time, material and components) is updated daily, weekly and 4-weekly. Powerful line management and a comprehensive and pragmatic planning are the key-functions to keep the work in schedule. In addition, the planning of the complete assembly is updated once per year for the entire W7-X. As many procedures are made the first time, there are often some changes in the processes. Therefore, the planning must be frequently updated. To keep the associated effort in reasonable limits, a foresighted and competent planning work is required. This needs staff which is exceptionally qualified and motivated. This concerns not only the compilation of planning but also the monitoring of the results and the optimisation of this planning.

At present about 100 technicians and engineers are working on the assembly. Another 30 to 50 may be needed in the next two years. Approximately half of the staff is hired from industry depending on the need. Additional experienced staff was seconded by other institutes, e. g. by the IFJ in Krakow. The co-operation between the internal and external staff proceeds smoothly. The special abilities and skills for the work on Wendelstein 7-X must always be considered.

3.8 Assembly schedule

The entire project schedule was revised in 2007. The main changes influencing the schedule are the omitting of 45 ports, the installation of an adiabatically cooled test divertor unit (TDU) for the first operating phase instead of the high heat flux divertor (HHF), an extended two shift work pattern in the assembly and additional assembly equipment for enhanced parallelisation of the assembly work. W7-X will be constructed in two stages. The first stage will be completed in 2014 and allows short pulsed operation at full power through the use of a simple adiabatic divertor. The second construction stage lasts one to two years. It contains mainly the completion of the in-vessel components, including the exchange of the adiabatic divertor with the water-cooled steady state divertor, and the associated cooling system. This upgrade allows steady state operation at full heating capacity.

4 Conclusion

The timely delivery of components for W7-X still requires stringent attention. The main components of coils, support structures, vessel and ports are no longer time critical but buffer times are not large. Other components like the helium piping, parts of the bus-bar system, the thermal insulation of outer vessels, parts of the in-vessel components and current feedthroughs are critical in terms of the schedule. The project is aware of the problem and takes appropriate counter measures.

The entire assembly was re-scheduled in 2007. A time buffer of more than a year on the critical path was implemented into the schedule, based on a risk assessment. In addition, the funding needed for this was considered. There are some remaining (smaller) components of which the detailed design is not complete. Also some assembly technologies (special ports, in vessel components) still have to be worked out. With still a considerable new procedures and technologies to be introduced it is considered likely that the existing time buffers will, at least partially, be needed.

At present the construction works are progressing as planned and the first main milestones of the assembly schedule were kept.

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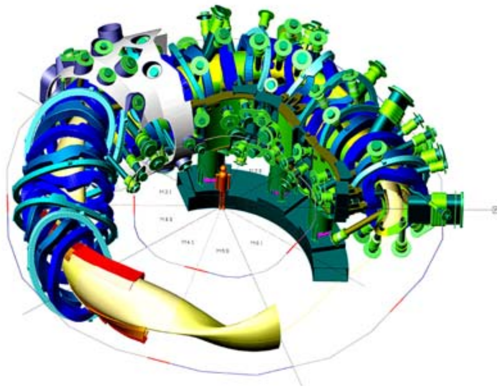

Fig. 1 CAD Model of Wendelstein 7-X

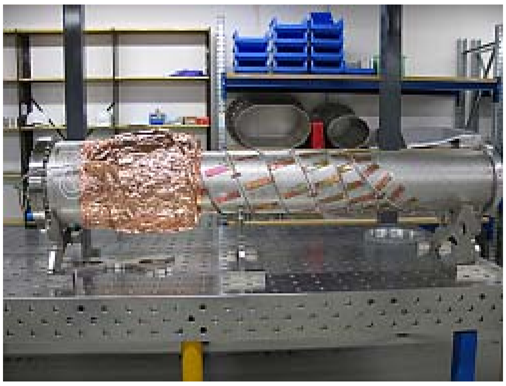

Fig. 2 Ports in preparation

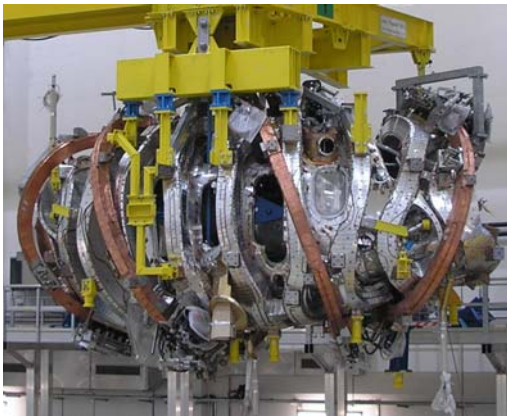

Fig. 3 The first magnet module of W7-X

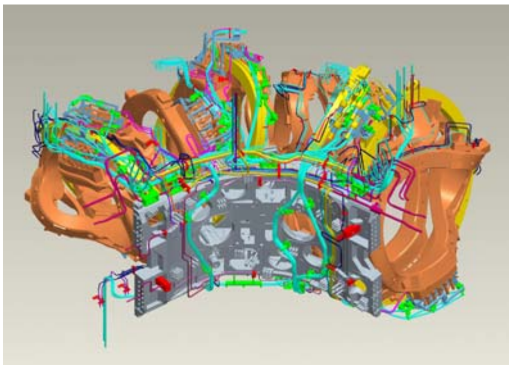

Fig. 4 Magnet module with bus-bars and helium piping

Fig. 5 A steel framework (TMV) stiffens outer vessel shells temporarily.

Fig. 6 First assembly work with in-vessel components

Figure Captions

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