Wendelstein 7-X - Status of the Project and Commissioning Planning

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The stellarator device Wendelstein 7-X (W7-X) is now in the final stage of assembly. All the machine components have been built and in mid 2014 the commissioning activities should start. The first objective of W7-X is to prove the stellarator optimization principles, i.e., to reach at least the same confinement quality as a similar sized tokamak. The second objective is to demonstrate stable high-power steady-state operation. In the present paper, after a short description of the device, the ongoing activities to complete the construction will be summarized, focusing on the optimization of the layout of the torus hall and on the completion and assembly of the in-vessel components. The main lessons learned during the assembly will be presented as well as the application of the quality control, the handling of non-conformities and the design change procedures. The planning of the commissioning sequences to perform the integral tests of the major W7-X systems is discussed in order to prepare the W7-X device to start plasma operation.

Keywords: Stellarator, Fusion experiment, Wendelstein 7-X, Assembly, Commissioning

1. Introduction

The Wendelstein 7-X (W7-X) fusion experiment is the next step device in the stellarator line of Max-Planck Institute for Plasma Physics and is presently under the final stage of assembly at the Greifswald site. W7-X will be the largest optimized stellarator in the world with a plasma volume of 30 m^3 operating a reactor-relevant plasma under steady-state condition [1, 2].

W7-X has been designed with the aim to show the viability of the optimized stellarator concept for future power plants. The first objective is to prove the optimization principles, i.e., to reach at least the same plasma confinement quality as a similar sized tokamak. The second objective is to demonstrate stable high-power steady-state operation. W7-X will also address the critical issue of plasma-wall interaction in long plasma pulses.

The main challenges in the construction of W7-X derive from the complexity of the 3D geometries, high dimensional accuracy required, the limited available spaces and the high loads in the magnet system [3].

The main parameters of W7-X are shown in table 1.

Table 1. Key engineering parameters of the stellarator W7-X.

Engineering parameter	Parameter value
Major radius	5.5 m
Minor radius	0.53 m
Number of non-planar coils	50
Number of planar coils	20
Number of current leads	14
Number of ports	254
Machine height	4.5 m
Outer diameter	16 m
Total mass	750 t
Total cold mass	425 t

The construction of the machine is almost completed [4-6]. A schematic diagram of W7-X is shown in Fig. 1.

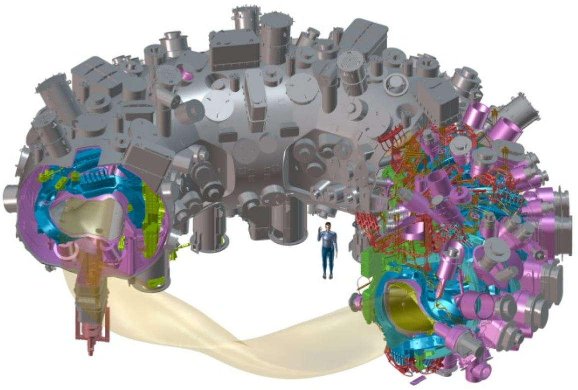

Fig 1. Schematic diagram of W7-X.

In order to start the commissioning of the machine and the plasma operation as soon as possible, it has been decided to start with a simplified configuration in the so-called Operational Phase 1 (OP1), which is divided in two phases: OP1.1 and OP1.2. The objective of OP1.1 is to measure the precision of the magnetic field and to test all the systems of the machine including periphery components, some basic diagnostics, the Electron Cyclotron Resonance Heating (ECRH) and the Control Data acquisition and Communication (CoDaC) system. The main goal of OP1.2 is to develop credible and stable discharge scenarios to demonstrate the feasibility to reach the stellarator optimized parameters (confinement and stability properties, divertor loads, high density discharges). The simplified configuration adopted in OP1.2 mainly consists in:

- installing radiation cooled Test Divertor Units (TDUs) allowing for 5-10 sec plasma pulses;
- installing heating systems with up to 8 MW of ECRH and 3.5 MW of Neutral Beam (NB);

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- installing a first set of diagnostics.

For the second operational phase (OP2) more heating power will be available and the TDUs will be replaced by the steady-state capable, actively cooled High Heat Flux (HHF) divertor able to withstand up to 10 MW/m^2. OP2 should demonstrate the high-power steady-state operation of W7-X and therefore foresees also ten cryo-pumps in the divertor.

2. The W7-X machine

W7-X is a superconducting fusion device with a five-fold magnetic field periodicity, which corresponds to five nearly identical modules, each consisting of two flip-symmetric half-modules with five different Non-Planar Coils (NPCs) and two different Planar Coils (PCs) each. The coil support structure of W7-X [7] is rather complex because it is the result of a compromise which guarantees the integrity of the magnetic system under limited deformations with acceptable stresses. Each PC and NPC is supported by the central support structure that has to keep the coils at their precise position. The Plasma Vessel (PV) has a shape that closely follows the twisted shape of the plasma cross section which varies between triangular and bean shaped. 254 ports are connecting the PV to the Outer Vessel (OV) and are divided in two types: diagnostic ports which also include plasma heating ports and supply ports. The thermal insulation, made by multilayer insulation supported by actively cooled thermal shields kept at 60 K by helium gas, is located around the PV, the ports and the OV. The plasma-facing components include the divertor made by target plates and baffle plates for an area of 19 and 33 m^2 respectively and the wall protection made by graphite tiles (inboard) and stainless steel panels for a total surface area of 115 m^2.

The basic coil system of W7-X [8] consists of 50 NPCs, 20 PCs and a bus-bar system connecting the coils of each type in series to their respective power supply through current leads. To energize the NPCs and PCs seven power supplies, independently adjustable between 0 and 20 kA, are used in order to achieve the required magnetic configuration. For each of the ten divertor modules a control coil is foreseen for strike-point position control. The control coils are made by water-cooled copper hallow conductor and are separately energized. Being located close to the plasma surface, the control coils can correct mainly the Fourier components B_{33} and B_{44} of the error field [9]. In addition five normal conducting so-called trim coils are installed outside the cryostat and are independently supplied in order to adjust the Fourier component B_{11} and B_{22}. Both sets of coils are used to correct asymmetries due to the tolerances of fabrication and assembly of the superconducting coil system.

The PV is composed of 10 half-modules. Each half-module is split into two sectors to allow the assembly of the first NPC and it is made by 20 stainless steel (SS) segments precisely bent and welded one to the other. The 254 ports have different forms; round, oval and rectangular; each one is equipped with a bellow to allow for thermal expansion during baking. Water pipe loops welded on the SS walls of the PV and ports are used for the baking at 150ºC and for the cooling during plasma operation. The PV is supported vertically by 15 legs which allow it to move radially during baking and to be adjusted vertically with respect to the coil structure by ±5 mm.

The In-Vessel Components (IVCs) [10,11] include the plasma-facing components (divertor targets, baffle modules, heat shields, panel wall protection and special heat shields in the Neutral Beam shine-through areas), a number of embedded diagnostics (Rogowski coils, Mirnov coils, diamagnetic loops), the control coils and the cryo-vacuum pumps. The divertor system consists of 10 similar units composed of nearly horizontal and vertical target modules and baffle modules adjacent to the target. The plasma vessel wall is protected by heat shields and water cooled stainless steel panels. The latter are located in areas well away from the plasma and are designed to remove an average heat flux of 100 kW/m^2. The low heat flux central part of the divertor (1000 kW/m^2), baffle (500 kW/m^2), and heat shields (300 kW/m^2) are built using the same basic technology: fine grained graphite tiles are mechanically clamped onto CuCrZr alloy heat sinks using TZM screws. The HHF divertor target elements are designed for a peak heat flux of 10 MW/m^2. The HHF divertor consists of 100 HHF target modules, 10 per divertor unit. Each module consists of a set of 8-12 target elements assembled onto a support frame and fed in parallel from a water manifold.

3. Assembly of the machine

3.1 Plasma vessel, outer vessel, ports

The PV consists of 20 sections. That enables the threading of the NPCs. Every coil requires a complex threading path (tilting, rotation, shifting) in all 6 degree of freedom. The minimal acceptable (theoretical) distance between coil and PV segment was set to 4 mm. Every PV section is insulated before it is moved to the assembly area. PV sections have to be connected to each other with an accuracy of about 2-3 mm. These sections are not very rigid because of the many openings for the later port installation. Dead weight deformations of the PV sections of up to 3 mm were observed. To compensate for it complex stiffeners had to be developed and optimized.

The first two sections are welded together once the first coil is threaded. Two sections represent a so-called half-module. The two PV sections have been aligned to each other and stiffened temporarily. The weld is made from inside and outside (X-prep, 17 mm wall thickness). The contour of the PV sections is surveyed by Laser Trackers (LT), checked against CAD requirements and the sequence of weld layers is adapted accordingly. Partial X-raying, helium leak test with local test chambers and the closure of the thermal insulation complete the work at this connection area. Six further coils are threaded across the two welded PV sections [12] (see Fig. 2). Thereafter all 7 coils are mechanically connected with each other forming one half-module of the magnet system.

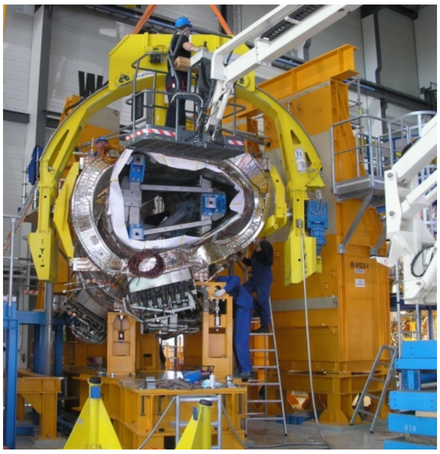

Fig. 2. Threading of non-planar coils over the PV.

Two half-modules are connected together forming a module of W7-X. The two PV half-modules are aligned to each other by means of a system of rods and bearing. The gap between both vessel parts must be as small and uniform as possible to minimize inadmissible contour deviations during the welding. On-site reworking of the gap is done in order to achieve this. Since the coils block access to the outer side of this connection, only welding from the PV inside (V-prep) is possible. Circular pipes were welded along the circumference at both vessel ends before they were pushed together. Once pushed together, the two pipes in contact and the surface made by the abutted vessel sections form a small, essentially triangular channel that is running around the weld seam area. That channel is filled with the shielding gas during the welding and with the tracer gas for the subsequent leak test. Once welded together, the PV module 3D-shaped as-built contour is scanned with laser scanning. A completed module is placed into the OV. Every OV module consists of an upper and bottom shell. OV shells (wall thickness 25 mm) are very flexible because of the about 100 openings for domes and ports. An outer stiffening frame enables the contour adjustment by means of about 25 pull/push rods. OV shells are insulated with multilayer insulation and an actively cooled shield made of brass.

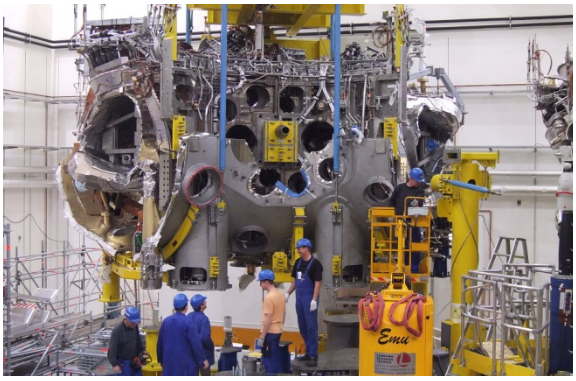

Fig. 3. An assembled magnet module in the lower cryostat shell on the way to its final position.

Except the first module all other modules must be moved together with the bottom OV shell in their final position onto the machine base due to the undercut between the ends of the magnet modules (see Fig. 3). As a consequence, the bottom shell (14 t) and the module (100 t) must be put together separately. Once the module sits in its bottom shell correctly, vacuum bellows are welded between the shell and the supports of the module. Successively the bottom shell, the magnet module and the PV module are separately aligned using the reference marks of the torus hall achieving tolerances better than 2 mm.

The assembly of about 50 ports per module is commenced when the modules of the PV and OV are in their final position. Ports need to be cut to length and shape according to the as-built geometry of PV openings and OV domes. The cut port is insulated with multilayer insulation and a brass shield and then positioned between PV and OV and tack-welded. A port weighs up to 1.5 tons and it must be maneuvered in all degree of freedom a few times until all connection works are done. Special assembly equipment has been built for this purpose (see Fig. 4). The welding of the ports to both the PV and the OV is a particular challenge. In order to be able to keep the tolerance for positioning and welding the port within 8 mm, the welders perform the welds and control the welding sequence according to online measurements with laser trackers. This welding procedure is applied sequentially at the inner side of PV and at the outer side of OV. For those ports whose orientation has to be adjusted after installation and welding, a correcting procedure was developed based on local machining and buffer welding.

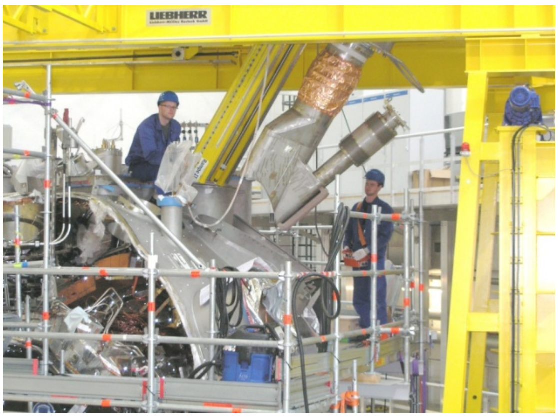

Fig. 4. The assembly of a port from the top.

The above work packages are repeated for all five modules of W7-X. A quite challenging task in terms of the cryostat is the connection of neighboring modules. 140 mm splice plates are customized and inserted at the so-called Module Separation Plane (MSP) and PV and OV are welded together simultaneously. To compensate for the weld shrinkage both modules are moved apart a couple of millimeters. At the last MSP the already welded 5 modules are forced apart by 8 mm to compensate for the weld shrinkage. The last extensive work package is the assembly of domes for Current Leads (CL). Their installation is as difficult as the port assembly. However, the overall accuracy requirements are much higher and the access for assembly equipment is very limited. Despite these increased challenges the first dome was already successfully installed. Six further CL domes are being assembled until March 2014. That closes the cryostat and enables its evacuation and commissioning.

3.2 In-vessel components

The IVCs assembly differs strongly from all other assembly works of the W7-X basic machine because the IVCs assembly area is encapsulated, the density of the components is high, there are increased cleanliness conditions and only few people can work in this area simultaneously. There is a logistics sequence of the IVCs assembly that cannot simply be changed or bypassed. Consequently, if a work package is blocked the entire assembly sequence is blocked. The positioning and welding of cooling circuits requires an unusual large effort. Particularly the interfaces between pipes, components and feedthroughs are work-intensive. Because of the limited space, hoses and bellows often cannot be used at these interfaces. Instead complexly formed mating parts are used, which often require reworks in the work shop. Orbital welds have to be performed at the inner surface or outer surface of pipes. X-raying at welds at the IVCs is nearly impossible because of the space restrictions. Therefore at every orbital weld the preparation must be intensively inspected before the weld can be done. Inspections with videoscopes after the welding are performed in most cases. Leak tests are also performed at all welds. The IVCs are installed with a typical geometrical accuracy of 1.5 mm which is a practical limit imposed by the given boundary conditions. The IVC are mostly fastened to the PV by bolts welded on the PV, about 1000 per module. They are positioned by means of manipulators or measuring arms, using predefined vector coordinates (see Fig. 5). The definition of the bolt vector coordinates and their length is a complex process. However, when a set of bolts is completely installed and free of faults the assembly of the associated components is a fast and robust process. 50 % of all bolts are placed by now and a majority of IVCs is assembled in two modules.

Fig. 5. Installation of in-vessel components.

3.3 Main lessons learned

1. The restricted place and the accessibility are the biggest time and cost driver in the assembly. Despite the W7-X complex geometry a larger distance between the components should have been recognized as essential early in the design.
2. Metrology (laser trackers, photogrammetry, laser scanning) must be used intensively to keep the position of components during the assembly and the welding under control.
3. Welded connections have to be designed such that the unavoidable shrinkage does not affect easily deformable parts in the direct vicinity. E.g. no simple openings in vessels but openings already strengthened by the supplier with flanges or pipe segments. Fillet welds have to be preferred on the construction site due to the complex geometries.
4. Pipe dimensions and clearances have to be designed such that commercially available welding equipment can be used. Orbital welds at the inside of pipes should be avoided.
5. Space and possibilities to bring shielding gas and tracer gas in the back of a weld must be considered.
6. A comprehensive assembly planning is necessary to have Quality Assurance and Assembly Plans (QAAP) ready in due time (see chapter 3.4).
7. A thorough assembly technology is necessary to have detailed work instructions and inspection instructions ready in due time since both are vital to assure the technical basis for the above QAAP.
8. It is important that specialized working groups in the assembly organization deal with the metrology, the vacuum technique, the welding technique and the periphery (cabling and piping).

3.4 The applied quality control system

Quality means not only the technical quality but also the organization with respect to documentation, proper handling of changes and deviations, assignment of responsibilities. Process instructions have been implemented to give clear rules for handling all processes, e.g. orders, supervision of the manufacturing and delivery, assembly, quality deviations and change requests. In order to be able to handle the rather complex execution of the assembly, a so-called QAAP (see above) has been developed for W7-X [13]. It contains all the essential activities and test planning including the input documentation, the responsibilities, and the output documentation such as test protocols and non-conformity reports. The main tests carried out during assembly are:

- for almost all weld seams the following have been preformed: (i) non-destructive tests such as visual, dye penetrant, ultrasonic, radiation; (ii) leak tests at all operating temperatures; (iii) pressure tests; (iv) magnetic permeability tests (base material $\mu_r \leq 1.01$, weld seams $\mu_r \leq 1.02$;
- geometry checks;
- collision investigations (at room temperature, during cool-down and at several load scenarios) on the basis of 3-D laser scanning or photogrammetry information and FE calculated component deformations;

- electrical tests of insulation like high voltage tests and Paschen tests;
- tests of all sensors;
- flow measurement of the superconductors and investigation of cooling channel obstructions;
- tests of the tightening of various bolts using ultrasonic method;
- cleanliness examinations with ultraviolet light (365 nm) to detect in particular organic substances, to ensure surfaces with a high vacuum suitability.

The quality assurance lab is equipped with the necessary devices to provide all the support activities.

3.5 Non-conformities and design change procedures

During the various phases of concept development, design, fabrication, assembly and even commissioning of the components there might arise causes that necessitate deviation from the original specification. Since these changes might impact the overall function of the device, the overall costs or the schedule until start of operation, they need to be properly managed by the project, agreed upon and documented (change management).

It is distinguished between changes and non-conformities. Changes are intentional deviations from an earlier defined specification. Non-conformities are observed unintentional deviations of a product from its specifications.

Intended changes of a specification are proposed to the project via a change request note. This note contains information on the reference specification, describes the proposed change including which organizational unit contributes what and the reasons for the proposed change. When the internal process is completed the chief engineer approves the proposed change on the basis of the comments that he has received and the responsible officer is asked to implement the change.

If a non-conformity of a component is observed, the severity is assessed and mitigating actions are developed. The chief engineer decides on the basis of the comments that he has received. During the assembly in case of minor or recurring deviations stop cards are used to temporarily suspend the assembly process, to document the deviation and mitigating action by the component team.

In case of urgent or very critical non-conformities or change requests the chief engineer can convene a meeting of the configuration control board where the changes or deviations are assessed, options are developed and high priority actions are implemented.

As of summer 2013 the total number of change notes is 1120. Of those 749 have been completely implemented, 214 are in the process of implementation, 135 have been declined or revised and 22 are being prepared. The total number of non-conformity reports is 2033 of which 1765 have been completely implemented. The number of stop cards is 3713. The number of topics that the configuration control board has dealt with is 172.

4. Torus Hall layout

The Torus Hall (TH) dimensions have been defined at the beginning of the project without a design of the main components (heating systems, diagnostics) and services (water cooling, cables, cabinets, vacuum and cryogenic systems) to be located around the W7-X machine. At present the space allocation and the design of the distribution of the services is a difficult and complex task considering the limited space (see Fig. 6) and all the boundary conditions (avoid collisions, accessibility for assembly and disassembly of non-permanent components, planned maintenance, safety paths). The main auxiliary structures in the TH are:

- The ground level platform consisting in four modules which are used to support a number of diagnostics such as the HEXOS spectrometer system. Below the steel flooring of the platform situated at 4.25 m from the TH floor a space 1.7 m high is used for the distribution of cable trays; vacuum, water and pressurized air pipes; gas supplies etc. to reach components on the platform or components located on the lower and middle part of the cryostat outer vessel.
- The Heavy Duty Structure (HDS) which consists of a central tower located at the center of the W7-X torus that is used to support water cooling pipes, helium quench exhaust system, vacuum piping, cable trays and other services and a beam for cable trays and vacuum lines that connects the central tower with the TH north wall.
- The Thomson Scattering Structure (TSS) is used as a support of the vibration sensitive diagnostics Thomson Scattering and Interferometers. It consists of a central column concentric to the HDS central tower, a bridge above the OV and an external column with a spiral staircase. The center of torus is accessible via the TSS. The TSS has no connection with any other structure or components to avoid any vibrations.

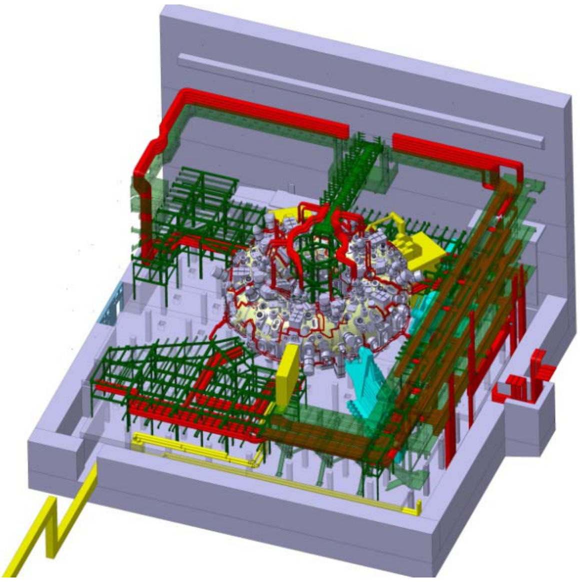

Fig. 6. The Torus Hall.

Among all services, the electrical system is probably the most complex one. A large number of cabinets (about 150) are located inside the TH on 3 levels near the east wall and in clusters on the TH floor or just outside the TH walls. The main distribution routing of cables (including fiber-optic cables) connects the W7-X machine with diagnostics, cabinets, and other electrical equipments. The cable tray routing has been designed in order to reach every area inside the TH and around the machine. All cables are classified into five different groups (power supply, signals, commands etc.) that are routed separately (except close to the OV) in order to reduce electromagnetic interference.

5. The commissioning of the machine

The commissioning of W7-X consists of two steps with increasing levels of system integration:

- the Local Commissioning (LC) which includes the final tests of a single component/system;
- the Integral Commissioning (IC) which includes all the necessary tests to prepare the machine for the plasma operation.

CoDaC plays an essential role for both commissioning steps. A task force has been established to plan the commissioning of W7-X [14].

5.1 The strategy

The IC strategy is based on the following considerations/assumptions:

- to start the IC as soon as possible in order to verify the status of the machine systems and their capability to reach the design requirements;
- to start the IC test of the cryostat and all the systems located inside, from the vacuum and cryogenic point of view, as soon as the assembly of such component is completed;
- to complete the installation of the in-vessel components without the TDUs but installing a temporary limiter in order to produce the first plasma in the OP1.1 phase;
- to install the TDUs after OP1.1, to perform the IC of the new systems (mainly some water cooling systems) in order to prepare the machine for OP1.2 plasma phase where the major parts of the scientific program related to OP1 phase will be implemented.

5.2 The planned IC tests

For the IC the following sequence of phases has been defined:

1. vacuum tests of cryostat;
2. cryogenic tests of cryostat;
3. normal conducting coil test;
4. plasma vessel vacuum tests;
5. superconducting coil tests;
6. preparation for the first plasma OP1.1

The vacuum tests of the cryostat will start in April 2014 and include the leak tests of all the welds related to the outer vessel, the water tubes of the plasma vessel and ports located inside the cryostat and the helium lines in the cryostat. In order to start the cool-down, the objective is to reach a vacuum of $1\text{x}10^{-3}$ mbar inside the cryostat within three days and to have a helium partial pressure in cold condition better than $1\text{x}10^{-5}$ mbar. The planned duration for this phase is estimated to be 19 weeks.

After the vacuum tests of the cryostat, the IC will proceed with the cleaning of the He cooling system, the cool-down of the cryostat (estimated duration four weeks) and the tests of three modes of operation of the cryoplant: simulation of 2.5 T plasma experiment without current in the superconducting coils, 10 K stand-by mode (typical for the nights and weekends) and 100 K stand-by mode (typical for long breaks within experimental campaigns). The main objectives in this phase are the following: to balance the different cooling circuits from the hydraulic and thermal point of view, to verify the thermal loads on coils, support structure and thermal insulation and to verify the stable operation of the current leads. The duration of this phase is estimated in 17 weeks.

The IC of the normal conducting coils (i.e. control coils and trim coils) includes the separate test of each coil unit up to the nominal current and the setting of the controller for the different phases (ramp-up, ramp-down and steady state). These tests are planned in parallel to the cryogenic tests.

The PV vacuum tests will start after the closure of the PV itself planned at the beginning of 2015 and include leak tests of flanges and seals of the ports and of the water and helium tubes inside the PV. During the first pump-down it is planned to reach 10^{-6} mbar within one week; later the same level of vacuum is expected to be reached within three days. After the first baking, it is planned to reach 10^{-7} mbar, and after conditioning of OP1 10^{-8} mbar. This phase is expected to take 10 weeks.

In parallel to the PV vacuum tests the IC of the superconducting coil system will take place. The IC includes:

- ramp-up and steady state at different current levels (2 kA, 6 kA) for each coil unit up to the maximum current compatible with the allowable deformations and stresses;
- test of all the coil units at the maximum nominal current (10 kA for PC and 14 kA for NPC) for the different magnetic configurations planned in the experimental phases OP1.1 and OP1.2;
- adjustment of the quench detection units;
- high voltage test.

The last IC sequence "preparation for OP1.1" includes:

- the magnetic surface mapping related to the planned configuration in the experimental phase OP1.1. This test consists in an electron beam that follows the magnetic field lines and is intercepted by a fluorescent detector in a fixed plane in order to create a 2-dimensional plot of the magnetic flux surfaces;
- baking of the plasma vessel;
- the IC of the glow discharges to be used in OP1.1 to clean the IVC and (if necessary) to boronize the plasma-facing surfaces, the gas injection systems and the essential diagnostics.

During the IC phases a large number of machine measurements will be taken with the objective to verify the thermal and mechanical behavior of W7-X and to validate the respective models.

5.3 The risk analysis

The main risk is related to leaks: vacuum leaks, water leaks and helium leaks. The most critical problem is the localization of leaks, in particular if such a leak is located inside the PV or the cryostat, due to the difficulty in reaching many areas. Also the repair action could be difficult in a number of cases. The additional risks in the cryogenic system are related to hydraulic problems (mass flow not uniformly distributed), non-uniform cool-down, hydraulic or thermoacoustic oscillations, pressure fluctuations.

The main risks in the superconducting coil tests could be due to:

- damages in the thermal insulation with consequent higher local heat loads on the superconducting coils;
- problems with the superconductivity of the bus bars (no current tests have been made so far);
- too high joint resistance of the on-site assembled bus bar joints and current leads joints;
- problems with the electrical insulation due to cracks after cool-down or movement during energizing;
- stability of the current controller.

In order to limit delays in replacing damaged components, an analysis of the essential spare parts is in progress.

6. Conclusions

The construction of W7-X is almost completed. The assembly of the cryostat is in the final stage. In April 2014 the integral commissioning of W7-X will start with the cryostat vacuum tests. The main objective is to produce a first-plasma in a limiter configuration in spring 2015. There is a number of lessons learned from the construction, assembly and preparation of commissioning of W7-X which might be useful for the construction of other large research devices. This is particular the case for the lessons related to the assembly of the machine, the organization of the work, the configuration control, the application of quality control and the management of non-conformities and design change procedures.

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