Experience Gained during Fabrication and Construction of Wendelstein 7-X

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Abstract. During the design and fabrication of the main components for the W7-X stellarator a number of technical challenges and severe problems had to be overcome many of which are considered relevant for other machines of similar size and complexity. Massive supporting structures are used to sustain the large electromagnetic loads. Finite element analyses (FEA) were used to design the main support structures. However, when the original FEA models were improved and refined, structural weaknesses showed up requiring reinforcement after components had already been fabricated. Some highly loaded elements are qualified by testing of instrumented prototypes. This proved to be very important to find and eradicate weaknesses. The coils for W7-X have been the subject of considerable delivery delays due to a variety of problems. In addition to the reinforcement of the coil support blocks on the non-planar coils, refined FEA showed that the planar coils undergo excessive out-of-plane bending. This has been corrected by additional shear pins to stiffen the casings. In an early stage it was decided that all 70 coils for W7-X should be cold tested. The cold tests have shown that of all the coils tested thus far the specified superconductive behaviour was according to specification. However, a number of faults have been found. These include cold leaks, poor performance of instrumentation, some of which is considered important for machine operation, as well as electrical insulation faults. After cool-down and warm-up in a test cryostat all coils are tested under Paschen conditions. Initially many non-planar coils did not pass this test. After returning to the factory detailed investigations have been carried out, repair procedures have been qualified and applied. Loss of time may partially be compensated by accelerating the assembly of the machine through the use of parallel assembly lines.

1. Introduction

The fabrication of W7-X components is well advanced and the assembly of the machine has started. During the manufacture and testing of components a considerable number of problems were encountered and had to be solved. Being a superconducting machine of size and complexity similar to ITER, KSTAR EAST etc., the lessons learned are considered to be applicable to these machines as well.

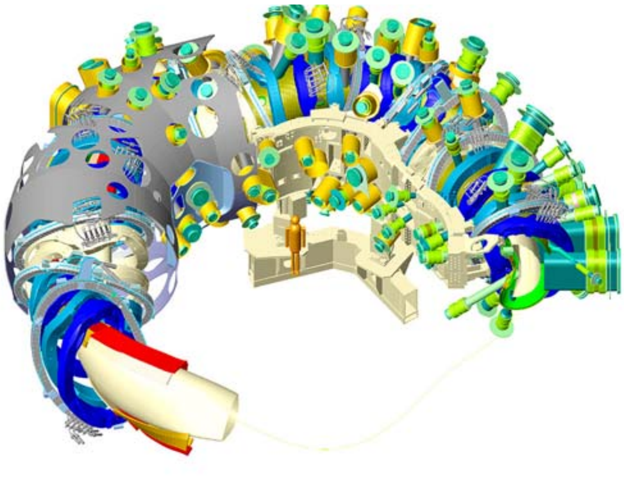

FIG. 1. Main machine layout.

W7-X is an optimised stellarator consisting of 50 superconducting non-planar coils (NPCs) and 20 superconducting planar coils (PCs) [1]. The W7-X layout is based on five-fold symmetry comprising five identical modules joined together to form a pentagon. Each half-module has five NPCs of five different types and two PCs, also of different type. The coils are connected by special bolts to a massive coil support structure, the central support ring (CSR), deployed at the inner radius of the machine. In addition several inter-coil supports, narrow support elements (NSEs) and lateral support elements (LSEs) are arranged between adjacent coils at the inner radius and the outer radius of the coil assembly respectively. Fig. 1 shows the arrangement of the main machine components.

The design of the coils is based on withstanding fast discharge voltages, also in so-called “Paschen-conditions” when cryostat pressure has risen into the lower mbar range.

2. Experience Gained during Design and Fabrication (Status mid 2006)

The design of the plasma vessel and cryostat vessel were completed at an early stage together with the design of the coils. The plasma vessel sectors have all been delivered. The fabrication of the cryostat vessel half shells is advanced. The general design of the thermal shield inside the cryostat is complete but detailed adaptation for different types of port and other penetrations through the cryostat vessel shell are still in hand. The design of the superconducting bus bars is complete and fabrication has started, but the detailed routing inside the cryostat of a number of cryogenic supply and return lines is still underway.

When the W7-X Project was set up, the approved resources of engineering manpower was inadequate. This has resulted, among others, in insufficient progress in the structural analysis of major parts of the rather complex W7-X stellarator. Due to time pressure manufacturing contracts were placed for coils, plasma vessel, cryostat vessel, the associated ports, as well as the central support ring before the structural analyses had been completed or validated. After due priority was given to this aspect end 2004, a strong in-house analysis group was set up. Its first major task was to generate a large global model of the main machine. This was validated by counter-checking and the results of the global model were then used as input to refined detail models of substructures that were generated and analysed by several institutes and companies throughout Europe [2]. It was found that for many components the structural loads were in reality nearly twice as high as had been assumed from previous work. Over the last two years this major analysis effort has continued, and is still not fully complete for the various support structures that must withstand the large magnetic forces and the dead weight of the machine [3].

FEA results showed that parts of the central support ring had to be strengthened (mainly by increasing weld thicknesses). As this involved the already machined first two half-modules, the reinforcement work had to be done in a very careful manner. Early 2006 it was completed successfully. In addition some of the support blocks on the NPCs were found to be structurally too weak and had to be machined off and replaced by new, more massive ones.

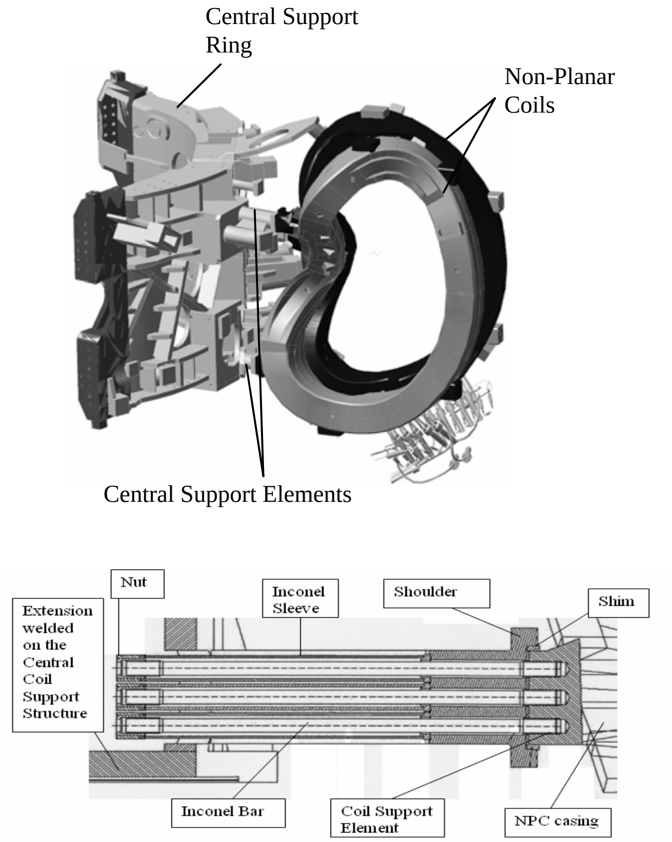

FIG. 2. NPC connected to the CSR, cross-section of a central support element bolted connection.

The bolted connections between the CSR and the coils are so-called central support elements (CSEs) that are designed in such a way that under the highest electromagnetic loads, when the coils show their maximum elastic deformation, partial opening of the contact faces occur and thereby ensure that the stresses stay within the allowables. Fig. 2 shows a picture of NPCs connected to the CSR. For the highest loaded CSEs it has been decided to further qualify them by testing of instrumented full or partial prototypes under simulated loading at cryogenic conditions in a mock-up. This has proven to be of paramount importance as weaknesses in the design showed up and could be improved once the problems had been understood.

A dedicated effort in design and analysis followed by qualification in mock-up tests of the NSEs has been undertaken and is still ongoing. In this design Al-bronze pads are used to limit the deformation of adjacent coils when they are energised. The relative movement of coils is lateral, as well as radial and includes also a small amount of rotational movement. The pads, therefore, have to sustain sliding and rolling movements under high contact loads (typical 100 tonnes). The pad surface is coated with MoS_2 through a PVD procedure and the counterface on the adjacent coil surface is polished and also MoS_2 coated by either spraying or by burnishing. Fig. 3 shows an exploded view of the pad arrangement.

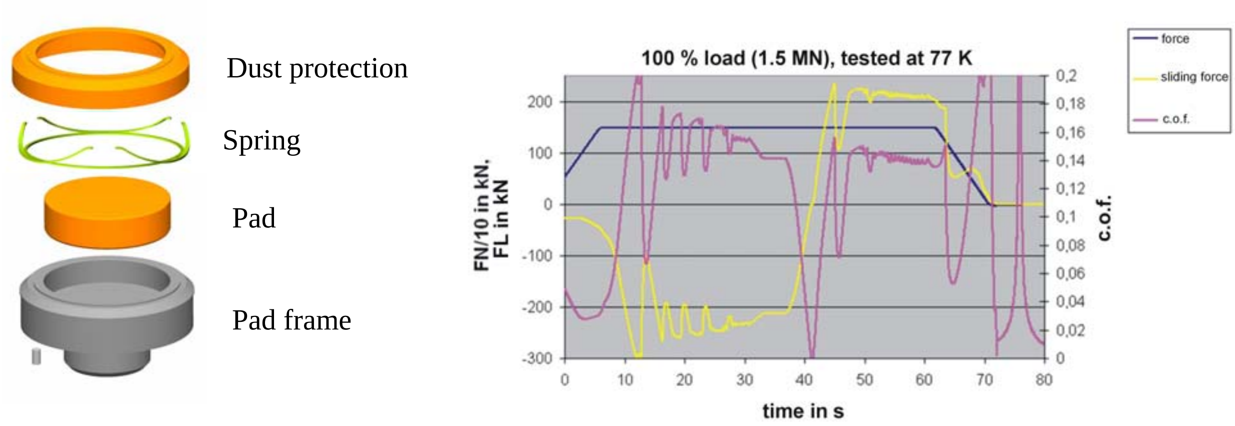

FIG. 3. Exploded view on NSE, graph showing stick slip.

The main problem encountered has been the occurrence of stick slip in the mock-up tests, conducted at 77 K, typically after more than 1000 – 3000 test cycles. This occurs when areas of sufficient size of the pads lose the surface coating. As it is feared that stick slip could induce a coil quench [4], the development objective has been to demonstrate that reliably more than the life cycles (~ 4000) can be obtained without the onset of stick slip. From the tests it can be concluded that the life cycles are not reliably reached without stick slip. To overcome the problem, two countermeasures are planned to be introduced: firstly to operate the machine such that the number of life cycles is reduced to about 1000, by only infrequently charging and discharging the coils instead of every morning and evening, respectively. As a consequence, man access to the torus hall will be severely limited. Therefore, nearly all electric/electronic cubicles that may require regular access have been located outside the torus hall. Secondly, a tubing arrangement has been included in the design of the pad systems that should allow, during long-term machine maintenance periods, to re-spray occasionally some lubricant into the pad housings. Moreover, tests are planned to induce simulated stick slip on a fully energised coil at 4 K in order to determine whether this really generates a coil quench.

The LSEs have been re-analysed and some were found to be too weak. This has necessitated to increase some weld seam thicknesses and to improve the design of a few types of LSE. As there is more room on the outer machine radius, where the LSEs are installed, as compared to the space for the NSEs, welded structures as well as bolted arrangements are used to provide solid connections between the coils. The design of particularly highly loaded types is being finalised and prototype mock-ups are being developed to qualify the assembly procedures.

After series production had started, FEA showed that the PCs experienced excessive out-of-plane bending. This has been corrected by introducing a large number (several hundred) of shear pins to stiffen the joint between the lateral plates and the internal and external circumferential plates of the casings. As some PCs had already been clad with copper plates, which provide the cooling of the casing, holes had to be drilled through the copper plates to allow drilling and reaming of the holes for the shear pins in the stainless steel plates underneath.

The space for the thermal shield between the NPCs and the plasma vessel is very limited as the coils are located very near to the plasma. Moreover, the available narrow gap requires that the change of contour of the plasma vessel in toroidal direction be closely followed by the thermal shield. Initially it was intended to use steel, brass or bronze plates that are pressed into shape and connected to stainless steel tubes with 50 K helium. It turned out to be impossible to develop the large amount of plates that are required to sufficient accuracy at affordable cost. Therefore, a new development was started based on forming multilayer glass fibre cloths, impregnated with epoxy, on moulds simulating the plasma vessel contour, with intermediate copper mesh to provide sufficient thermal conductivity [5]. The outer layer consists of Al-foil to provide low emissivity. The internal layers are formed by multilayer insulation of Al-foils to minimise the amount of thermal energy transfer from the plasma vessel wall. At several locations, the copper mesh is connected with the stainless steel cooling tubes via copper straps. The shields are fastened to the plasma vessel using distance holders of a low thermal conductivity material. This novel development has proven very successful and was developed jointly between W7-X and the manufacturing company supported by cryogenic experts. The internal thermal shields of the cryostat vessel consist of a more conservative design based on copper plates cooled by 50 K helium.

The design of the gravity supports for the vessels and the CSR together with the magnets is complete and manufacturing contracts have been placed. As it is of utmost importance that some of the in-vessel components, e.g. divertor, are in the exact correct location with respect to the magnetic field, the design of W7-X incorporates the possibility to adjust the location of the plasma vessel as a whole within a radius of 5 mm with respect to the coils and cryostat vessel. The plasma vessel supports have, for this reason, been designed as pendulum supports with very low friction for lateral movement. The exact details of the adjustment system are still being further developed in conjunction with experts from Rostock University.

The design of the in-vessel components is in an advanced state and the qualification of the high heat flux (HHF) elements, the so-called target elements, of the divertors by testing of prototypes in a HHF test stand is underway. Testing of a first test series was unsuccessful as the interlayer between the carbon fibre graphite composite target material and the water-cooled copper alloy substrate showed a high failure rate (cracks). It was also shown that various novel non-destructive test methods were insufficiently reliable to detect the cracks and hence it will be necessary to test each target element in a HHF test facility before it can be assembled into a divertor [6]. This large test programme had not been foreseen originally. Production of series elements will commence as soon as newly fabricated prototype elements pass the HHF tests.

Diagnostic design is ongoing so that the initial set of diagnostics will be available in time for installation in the machine [7].

The design of the additional heating systems is very advanced for the electron cyclotron resonance heating system, where many components have already been installed and tested [8]. The design of components of the neutral beam lines will be mainly copied from the ASDEX-Upgrade machine and installed to be available at the start of plasma operations or a short time thereafter. The ion cyclotron resonance heating system will be designed and installed later.

Power supplies for the coils and for other major systems are installed and tested [9]. As for the balance of plant, the design of the cryoplant is nearly complete and fabrication has commenced. The secondary water-cooling system is partly installed and the design of the primary systems is nearing completion.

3. Experience Gained during Testing of Components

For key components prototype units were fabricated and tested (NPC, cryostat vessel). In many cases manufacturers were encouraged to propose alternative cost-effective solutions. For the NPCs this led, among others, to the change from forged to cast casings. The manufacture and testing of the superconducting coils for W7-X has been particularly problematic and this section deals predominantly with the experience gained during their manufacture and testing.

The series production of the NPCs has been severely hampered by design faults and manufacturing mistakes. As a result the coils for W7-X have suffered large delivery delays.

In an early stage it was decided that all 70 coils for W7-X should be cold tested. The original rationale was to ensure that the superconducting properties should be checked against the specification. The cold tests conducted so far have shown that none of the coils showed problems in this respect. However, a number of faults have been found that without the cold tests would not have been detected. These include cold leaks, poor performance of instrumentation as well as electrical faults. The coils had originally been specified to be “Paschen-tight”, but no special tests had been foreseen to demonstrate this. Only after the ITER toroidal field model coil had shown a Paschen failure, experts advised the W7-X Project to introduce Paschen tests. This was done at a time coil production was already well underway. Before the NPCs leave the manufacturer they are Paschen tested in a vacuum tank at room temperature and then delivered to a cold test facility at CEA Saclay, near Paris. Here they undergo testing at 4 K under maximum current conditions, as well as Paschen testing after warm-up in the test cryostat using a voltage up to 9.1 kV. The PCs are Paschen tested up to 6.3 kV. It was found that many coils did not pass the Paschen test. These coils were sent back to the factory for detailed investigations and repair. Early 2006 it was established that 2 types of NPC had a systematic problem caused by cavities in the epoxy filling in the so-called connection area where conductors join and emerge from the winding pack. The cavities are caused by a fault in the impregnation procedure, which for two of the five types of NPC has been done in an unconventional manner, which had obviously not been properly qualified. Fig. 4 shows systematic impregnation faults in the connection area of a NPC. After the Project had understood the nature and cause of the faults, all the affected coils and the not yet embedded winding packs were investigated and repaired which includes the filling of the cavities by charged resin. Following their repair they will be re-tested at low temperature followed by Paschen testing. The reason why the Paschen discharge occurred in the two types of NPC is that where conductors penetrate through the cavities the turn insulation (0.6 mm nominal) is insufficient to sustain the 9.1 kV test voltage under “Paschen conditions”, whereas in vacuum or at atmospheric pressure much higher voltages can be sustained. Air can penetrate into the cavities due to the fact that the charged epoxy resin, that fills the connection area, disconnects from its stainless steel collar during cool-down. Through the resulting small

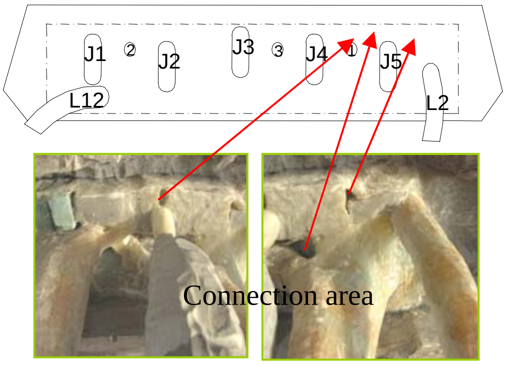

FIG. 4. Systematic faults in a NPC.

gap air can penetrate and fill the cavities, when at the same time cracks exist which connect the cavities with the gap. The identification of the various faults and the subsequent repair, aggravated by a half year shut-down of the cold test facility due to an oil leak, has led to delays of nearly two years.

The square section jacket of the NbTi superconductor is of Al-alloy. Welding of the Al-jacket to bought-in Al-stainless steel transition pieces, which is necessary for every superconductor joint (several hundred in W7-X), has shown to be difficult. During heat input impurities evolve both from the superconductor wiring and from the Al-jacket. This leads to porosity in the weld and sometimes to leaks, although the structural strength of the weld remains adequate. Stringent cleaning improved the situation for the wiring but not for the jacket. Only after approximately 0.3 mm of the external jacket surface are removed by scraping significant improvement is achieved. This is believed to be due to impurity inclusions that result from the jacket extrusion process. However, even with these measures variations in weld quality are observed, which may be the result of variations in the hardness of the Al-alloy.

An additional problem that was found is related to the cast casings of the NPCs. During machining some cavities were detected inside areas with large wall thickness, which could not be checked with radiography. It was then decided to have all casings tested for hollows by means of a linear accelerator. Unacceptable faults have been found and have subsequently been repaired by welding.

A large number of pure copper strips is attached by welding to the stainless steel coil casings to remove thermal energy from the casing and conduct it to 4 K helium routed in stainless steel tubes. The joint between the strips and the tubes is by soldering. This requires an aggressive flux in order to remove the oxide layer from the steel. After soldering surplus flux is removed by steam cleaning and other methods. It has been found, however, that remnants of the flux, in form of hygroscopic salts, are still present in small pockets in the soldered joint. It was feared that this could lead to pitting corrosion when the hygroscopic salts are not fully encapsulated and have contact with the humidity in the air. When the flux remnants were discovered, a different soldering procedure was qualified that avoids the use of aggressive flux. However, at that time already 15 coils (as well as a large number of ports for the plasma vessel) had already been completed with the former procedure and the replacement of the tubes would have imposed another very long delay for the Project. Therefore, it was decided not to replace the affected tubes and to minimise the risk of corrosion by decreasing the moisture content in the air. This is done by storing components in plastic bags with desiccant and by keeping the relative humidity in the assembly hall below 50 %. Furthermore, as a drastic fall back measure, plasma operation without coil casing cooling is being investigated by reducing the thermal energy that is intercepted by the casing by applying a near 100 % highly reflective surface by adhesion of Al-foil, as well as by increasing the cooling of the winding pack.

4. Assembly of the W7-X Stellarator

As the progress of machine assembly is dictated by the delivery of main components, the delivery delays described in the previous sections have resulted in the assembly being on hold and delayed by at least two years. In a recent internal review assembly sequences have been re-studied, including the incorporation of experiences gained in the assembly of a few coils. During the last two years complex assembly sequences, including the installation of the large number (299) of ports in the plasma and cryostat vessel walls, have been studied in detail. The updated sequences now show that the overall assembly duration is extended by a considerable amount. Moreover, in the updated schedule, time contingencies have been proposed for very complex procedures and for procedures that have not yet been studied (mainly those that occur in the last phase of the assembly). The overall result shows a much later completion date than hitherto assumed.

To minimise the overall delay in the start of plasma operation, assembly accelerating measures have been studied. Whilst some time can be gained by omitting some components, this would lead to a severely downgraded performance of the machine and long shut-downs later to upgrade the performance. Hence this has been rejected. Instead, it was found that nearly two years of assembly time can be gained if certain assembly sequences can be conducted in parallel so that work on two modules can proceed simultaneously. These sequences include the stringing of coils over the plasma vessel sectors and the connection of the coils to the central support ring, as well as the joining together of two half-modules to form a single module. These assembly sequences are carried out in the assembly hall. As its floor space is already occupied by existing assembly stands, another assembly hall will be needed for parallel work. Assembly sequences that follow those described above cannot be duplicated as these must be undertaken in the torus hall and its floor space is already fully occupied with existing assembly stands that provide a single assembly line.

As there is no suitable building in W7-X for a second assembly hall, and the building of an additional hall is expected to take too long due to lengthy approval procedures, etc., it is planned to use an existing spare hall of a nearby decommissioned power plant. Its refurbishment, the procurement and installation of the necessary assembly stands, tools and equipment will take approximately one year. The doubling of the assembly capacity of coils, makes, of course, only sense if it is certain, that the series production of the coils can proceed without further problems. It is assumed, that with two parallel assembly lines approximately 34 coils per year can be assembled. To sustain this rate of coil delivery, it is not only required to increase the production rate, but also the cold test rate. The limit of the Saclay facility is approximately 22 coils per year. A second, suitable coil test facility does exist within Europe, namely the TOSKA facility in the Research Centre in Karlsruhe, Germany. However, this facility has been mothballed for a number of years and its control system is outdated (25 years old). To refurbish the TOSKA facility also about one year will be required. Therefore, the possibility exists, in principle, to accelerate the assembly of the W7-X machine by about two years. The pre-requisites are, however, the increasing of the production rate, the addition of a second cold test facility and the availability of a second assembly line.

5. Conclusion and Recommendation

Prototype testing of key components, like coils, heavily loaded structural components, etc. is important to demonstrate the principal feasibility of the design. However, for the series production it is often common to introduce, for various reasons, changes with respect to the prototypes, which can reduce the validity of the prototype tests by such an amount, that tests should be repeated. Moreover, in W7-X it has been found necessary to introduce changes after component fabrication had already started.

For a complex first-of-a-kind machine, like the W7-X stellarator, the experience has shown that:

(i) It is essential that at the start of such a project a thorough and honest estimate is made of the manpower requirements for the various stages of the project and that manpower of adequate quality and quantity is recruited. In W7-X this was only done at a late stage and has contributed to the existence of several problems.

(ii) It is essential to have adequate expertise within the project team to ensure that the designs elaborated within the project are sound and that design and manufacturing proposals by manufacturers can be thoroughly reviewed by experienced and knowledgeable engineers and scientists. It is of utmost importance that the project is fully aware and understands the risks involved in the fabrication and test procedures that are commonly agreed. Although design reviews with external experts are a useful tool to find weaknesses in designs, in-house expertise is needed to control and supervise the work in-house and in factories.

(iii) The engineering design of main components must have reached a mature status before manufacturing contracts should be placed.

(iv) A thorough investigation of the preparedness of industries for the manufacturing and testing contracts is essential in judging the quality of work that can be expected from them as well as the expected punctuality of deliveries.

(v) Instrumentation must be qualified for its intended use by testing under simulated conditions.

(vi) Cold testing of coils, at least one or a few of each type, has been found to be mandatory in W7-X. Submitting coils to a few charge/discharge cycles at low temperature has been found useful in detecting manufacturing weaknesses [10].

(vii) Tests in Paschen conditions after at least one cool-down/warm-up cycle are highly recommended.

(viii) Divertor target elements should be tested in a HHF test facility prior to be assembled into components.

(ix) Significant acceleration measures for machine assembly are possible by parallel work, but this will incur considerable additional investment costs.

It is recommended that above experience be used for other machines and that in particular for fusion machines of complexity similar to W7-X cold testing of at least one coil of each type be carried out followed by tests in Paschen conditions.

6. References

[1] WANNER, M., Construction and Assembly of Wendelstein 7-X, 15th International Toki Conference, Fusion and Advanced Technology, Toki, 2005 (to be published).

[2] GASPAROTTO, M., et al., The Wendelstein 7-X Mechanical Structure Support Elements: Design and Tests, Fusion Engineering and Design **74** (2005) 161-165.

[3] BYKOV, V., et al., Structural Analysis of W7-X: Main Results and Critical Issues, 24th Symposium on Fusion Technology, Warschau, 2006 (to be published).

[4] SCHAUER, F., Optimization and Stability of a Cable-in-Conduit Superconductor, IEEE Transactions on Magnetics **32** (1996) 2760-2763.

[5] SCHAUER, F., et. al., Thermal Insulation of the Wendelstein 7-X Superconducting Magnet System, Proceedings 20th International Cryogenic Engineering Conference (ICEC 20), Beijing, 2004, 853-856, Eds. L. Zhang, L. Lin, G. Chen, Elsevier Ltd., Oxford, 2005.

[6] BOSCARY, J., et al., Results of the Examinations of the W7-X Pre-series Target Elements, 24th Symposium on Fusion Technology, Warschau, 2006 (to be published).

[7] HARTFUSS, H.-J., et al., Diagnostics for Steady-State Plasmas (to be published in Plasma Physics and Controlled Fusion).

[8] ERCKMANN, V., The 140 GHz, 10 MW, CW ECRH Plant for W7-X: A Training Field for ITER, this Conference, Paper IT/2-4Rd.

[9] RUMMEL, T., et al., Acceptance Test of the First Power Supply and Protection System Module for W7-X, IEEE Transactions on Applied Superconductivity **16** (2006) 747-750.

[10] SBORCHIA, C., The Manufacture of the W7-X Superconducting Magnet System as Relevant Experience for the Construction of the Next Fusion Devices, Applied Superconductivity Conference, Seattle, 2006.