The construction of the Wendelstein 7-X stellarator

T. Klinger for the Wendelstein 7-X team

Max-Planck Institute for Plasma Physics, Greifswald, Germany

e-mail contact of main author: thomas.klinger@ipp.mpg.de

Abstract. The construction status of the large superconducting stellarator Wendelstein 7-X is reported. The manufacturing and tests of the main components are reviewed and major design tasks during the device assembly phase are summarized. The assembly is currently proceeding on three out of five assembly stands. Four out of ten magnet half-modules are completed. Major work packages are the electric and cryogenic connection of magnets, support ring and thermal shield. Other main tasks are the thermal insulation, the port assembly and the manufacturing and assembly of the actively cooled in-vessel components. The construction work is well on track and the assembly will be completed in mid 2014 as planned. A staged approach to steady-state operation with 10MW heating power is presented, where the key element is an inertially cooled test-divertor unit for the development of high-power steady-state scenarios. It is replaced after a first short-pulse operation phase by the actively cooled divertor.

1. Introduction

An integrated stellarator concept with fusion power reactor potential requires optimization. Considerable progress has been made with the optimization of plasma discharge scenarios in modern heliotron devices like LHD [1]. In particular, very high densities could be achieved (no Greenwald limit) and magneto-hydrodynamic (MHD) instabilities at high plasma-β turned out to be relatively harmless [2]. However, it appears to be difficult to find integrated scenarios with fusion relevant parameters. The Wendelstein 7-X device follows a concept to optimize the magnetic field configuration using non-planar modular coils [3]. Optimization means here to create a vacuum magnetic field that confines fusion plasmas and simultaneously guarantees (a) good, nested magnetic surfaces, (b) good MHD equilibrium and stability, (c) low neoclassical transport in the long-mean-free-path-regime, (d) good confinement of fast particles. Another optimization element is to (e) minimize the bootstrap current in order to reduce changes of the ι-profile during a discharge. Based on the general principles of quasi-symmetry and iso-dynamicity [4], a suitable low-shear magnetic field configuration could be found and forms the basis of the present Wendelstein 7-X design.

The predecessor device Wendelstein 7-AS (in operation until 2003) has successfully proven the high potential of the above-described approach [5]. Wendelstein 7-AS was the first stellarator device based on non-planar magnetic field coils. Even though the magnetic field was only partially optimized, its performance parameters were significantly improved compared to any other stellarator device of similar size. During the last two years of operation the island divertor concept was investigated [6] and new, promising operation regimes where discovered [7].

The main advantage of stellarators – in addition to the absence of neo-classical tearing modes, current disruptions, and violent edge-localized modes – is the inherent steady-state capability. The plasma equilibrium is mainly defined by the stellarator vacuum magnetic field and not by a complex self-organization process as in tokamaks or reversed-field pinches. Furthermore, no strong current drive is required, something that was not yet proven to be feasible with sufficient efficiency. To demonstrate steady-state plasma operation at fusion-relevant parameter values, the first wall, the divertor and all other plasma facing components (e.g. mirrors, shutters, and optical elements) must be water-cooled. In addition, heating systems – in our case the electron-cyclotron heating – and diagnostics as well as data acquisition and control must be designed for long plasma operation. It is the main scientific mission of Wendelstein 7-X to demonstrate the reactor potential of optimized stellarators and to contribute to the development of the technologies required for steady-state operation of fusion power plants.

2. Design and configuration

All components of the device are designed using 3d-computer-aided-design (3d-CAD) tools, mainly CADDS5 and CATIA-V5. The design work is organized in a central CAD-office where the priorities are set according to the actual requirements. All documents concerning the project, including all CAD-models and -drawings, are stored in a central document management system to ensure model consistency and proper information flow.
It is of utmost importance to establish a formal configuration control (CC) and configuration management (CM) system. The available space in the cryostat volume is very limited and changes easily lead to unacceptable collisions. Also for quality assurance in general, CM is absolutely required. Fig. 1 shows a detail of the design in the cryostat. To make a correct design space analysis, further information is required: (a) the actual as-built geometry of *all* components and (b) finite-element (FEM) calculation based analysis of the movement of components due to magnetic forces, vacuum and thermal expansion. For that, the following tools have been developed and implemented:

- a full metrology system based on laser trackers, scanners and photogrammetry,
- a back-office to process the data and to create the as-built models,
- a suite of FEM-models for all components under mechanical loads.

Any design change and any deviation from the CAD-geometry is analyzed for collisions and structural stability, based on FEM (often global) model calculations made for the as-built geometry. A change is only released after an acceptable design solution has been found that is compatible with the different magnetic field configurations of Wendelstein 7-X.

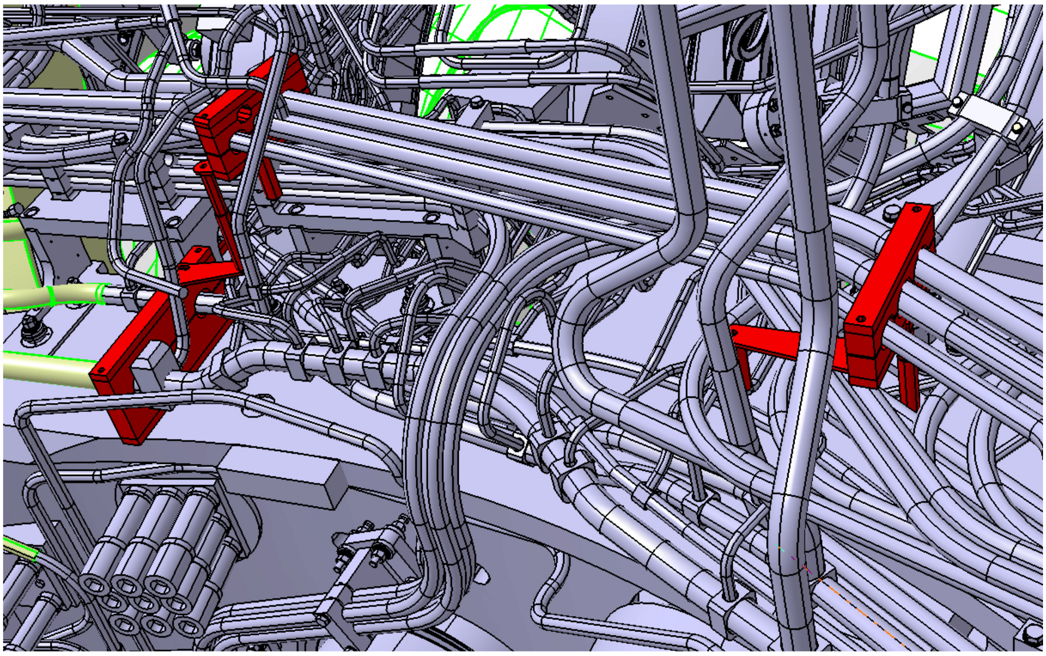

FIG. 1. Detail of the design of Wendelstein 7-X. Shown are the Helium supply pipes and the super-conducting bus bars together with the required holders and clamps (in red). Also shown is part of the central support ring with the super-bolts (bottom left).

3. Manufacturing and test of major components

The manufacturing and delivery of the superconducting magnets (50 non-planar coils and 20 planar coils, about 3m diameter each) and necessary reinforcements of major structural elements of Wendelstein 7-X have been the cause for considerable project delays. The issues related to these technical difficulties are now resolved. Nevertheless the timely provision of the device components remains being a major challenge.

3.1. Magnet system

The manufacturing of the superconducting magnets has been finished. All coils are tested under cryogenic conditions to verify the specified mechanical, hydraulic, electric and superconductivity properties. Severe quality deviations were found in the cast steel of the coil casings (voids), the impregnation of the winding packs (cracks and voids) and in the helium supply lines (leaks). Paschen-tests at 9.1kV DC before and after cool-down turned out to be of great value in detecting insufficient high-voltage insulation of the coils (in case of a quench up to 2.5kV can occur). A quench test has been made for each coil at nominal current of 17.8kA. The superconductivity properties turned out to be always according to specification. A comprehensive survey of manufacturing and test of the Wendelstein 7-X magnets is found in Ref. [8]. At the time of submission of the manuscript, 49 out of 70 coils were successfully tested.
The electromechanical forces on the magnets are considerable (of the order 100t) and it is a difficult problem to ensure the structural stability of the global magnet system (at 3T nominal magnetic induction on the axis). An in-depth analysis based on various local and global FEM model calculations was necessary to optimize the load distribution between the various support elements. The design of the support concept for the magnets is now frozen and device operation limits are unlikely to occur. It consists of a combination of a massive central steel ring (10 half modules in total), bolted central support elements connecting the coils to the ring, and distributed local support elements (partly welded, partly bolted, partly sliding/tilting). The actual weight of the magnet system (425 tons) is carried by 10 vertical cryo supports.
The magnet system has five different types (shapes) of non-planar coils and two different types of planar coils. Coils of each type are connected in series via superconducting bus bars. The 24 bus bars of the first module are delivered (Research Centre Jülich, FZJ) and assembled by the use of about 100 mechanical support elements (85 different types connected to support structure and coils). Each of the 7 coil groups is connected to the respective 18kA power supply via a pair of current leads (about 2.5m long and 500kg weight). The current leads form the interface between the warm end (power supply) and the cold end (bus bar). They are installed with the cold end top, the latter making a new development and tests necessary (Research Centre Karlsruhe, FZK).

3.2. Cryostat

All ten half modules are manufactured and are successively prepared for assembly. The 254 ports (1.5 to 2.5m long, weight between 100kg and 1t) are manufactured and in the assembly preparation, too. The first module of the outer vessel was delivered; the next modules either passed already the acceptance test or are in advanced stages.
A major and quite demanding work package is the thermal insulation. The thermal insulation of the first module and of the two following half-modules of the plasma vessel is complete, including brackets, domes, cryo shield, and helium pipes and manifolds. The shields are made

of epoxy impregnated glass fibre panels with integrated copper meshes to provide good thermal conductivity. They are cooled with Helium flowing through pipes attached by copper braids. Between the shields and the warm walls, 20 layers of Aluminium-coated Capton® foil are placed. The design and the manufacturing of the thermal insulation of the outer vessel and the ports are in progress. This turned out to be a challenging task due to the complex shape of the components and the very restricted space in the cryostat (cf. Sec. 2). The thermal shields of the outer vessel and the ports are made of copper or brass.

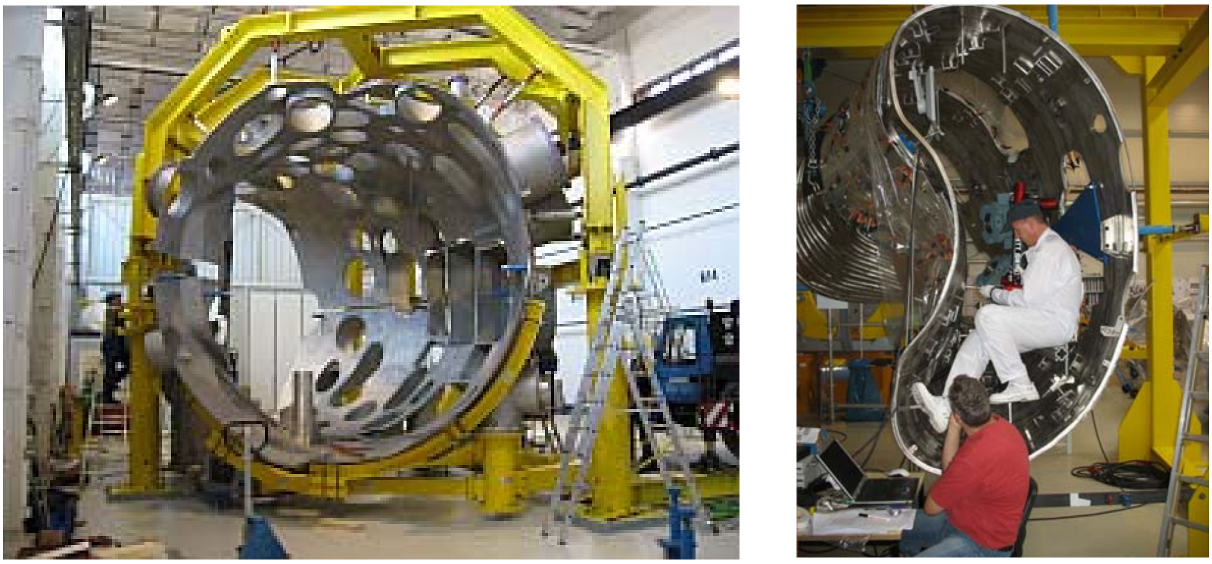

FIG. 2. Outer vessel module (left picture) and plasma vessel module (right picture). Shown are the handling of the outer vessel shell and the first installation trials for the in-vessel components.

3.3. In-vessel components

The in-vessel components comprise wall panels and heat shields for the wall protection, the 10 divertor modules (top/bottom) with baffles and horizontal and vertical closures, sweep coils and cryo pumps. A complex cooling pipe system, sensors, cables and some embedded diagnostics complete the system. The high heat flux (HHF) divertor target elements (Plansee) are made of carbon-fibre composite (CFC) that is electron-beam welded to a copper chromium zirconium base structure. They were successfully tested with 8500 load cycles.

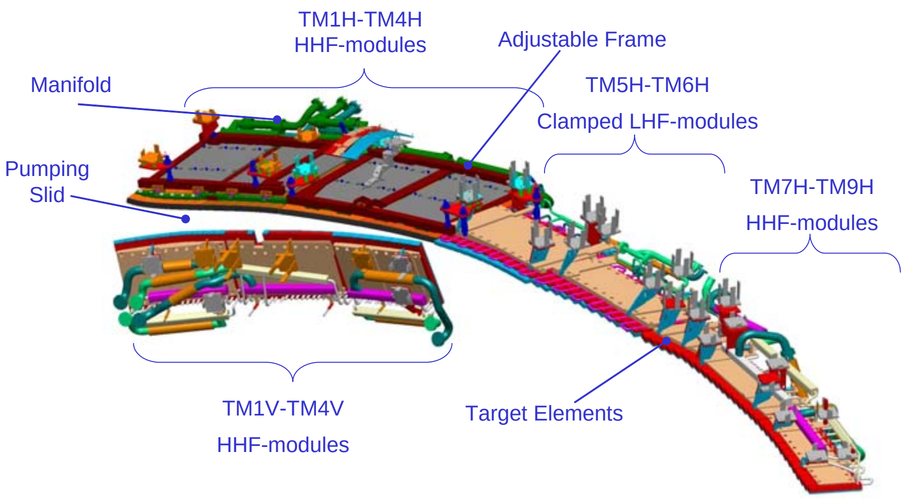

FIG. 3. CAD model of the divertor target module with support elements and cooling lines (partly). HHF = high heat flux, LHF = low heat flux

The actual island divertor is designed for steady-state operation at 10MW ECRH heating power and additional 10s pulses of 20MW NBI and 4MW ICRH heating power. The heat power flux is mainly transferred to the target plates (up to 10MW/m^2), but partly also to the baffle plates (up to 0.5MW/m^2) and to the wall protection shields (up to 0.3MW/m^2). All in-vessel components are actively water cooled. Fig. 3 shows a CAD model of one of the divertor modules.
The first operation phase of Wendelstein 7-X will be restricted to 10s-shots at 10MW heating power (see Sec. 5). This allows one to explore magnetic configurations and plasma scenarios suitable for steady-state divertor operation. For this purpose, an inertially cooled test divertor unit based on conventional technologies is designed and manufactured; it has the same geometry as the actively cooled divertor.

4. Device assembly

Currently about 100 technicians and engineers work directly on the assembly of Wendelstein 7-X (the figure will increase by 30-50 within the next two years). About half of the staff is hired from industry. The work is organized in two shifts and six day per week and requires strict on-site and off-site organization and leadership.
All assembly work has been distributed logistically on seven mounting stands. In this way some work packages can be done in parallel to save time. The different mounting stands are used for (a) pre-assembly of the magnet half-modules, *i.e.*, coils, plasma vessel sectors, support structures, (b) module assembly including bus-bar and helium pipe system, (c) final assembly of the modules with outer vessels, vertical supports, current leads, and ports. Fig. 4 shows a photo of the first two assembly stands. Because of the very narrow installation space, massive use of 3D measurement techniques is required, e.g. laser tracker, photogrammetry, laser scanner. The welding engineering is demanding and ranges from the aluminium jacket of the superconductor to connections of the steel structure components with up to 25 mm of welded seam depth with an accuracy of less than one millimetre been adhered to.

FIG. 4. First two assembly stands for the pre-assembly of the magnet system, the installation of the support elements and part of the Helium pipes and the bus bar system.

4.1. Magnet modules

As for now, 4 out of 10 magnet half modules are completed. A complex technology for the assembly of the central supports and the inter-coil structure (cf. Sec. 3.1) was developed and successfully implemented. The technology entails the measurement and manufacturing of 14 shims and 50 wedges. The wedges are fitted and welded under strict position control. Welding the lateral supports is also carried out via a specific control of the weld shrinkage. The series assembly of magnet modules continues. Fig. 5 shows a complete magnet module of Wendelstein 7-X (view from the low-field side). Visible are the 14 non-planar and the 4 planar coils (the latter with copper cladded casings), the vessel, thermal insulation, supports.
For the bus bar assembly, the support brackets are positioned precisely and fixed, the pre-fabricated bus-bars (lengths between about 4 m and 14 m) are threaded and stacked in the support bearings and clamped together. Finally the superconductor joints are installed to connect bus-bar ends and coil terminals electrically and hydraulically. The installation of the helium-pipe system has turned out to be as demanding as the bus-bar system. Batches of precisely pre-bent (+/- 2 mm) pipes are positioned above and below the bus-bar system. The pipes are then fastened at the coils and structural elements.

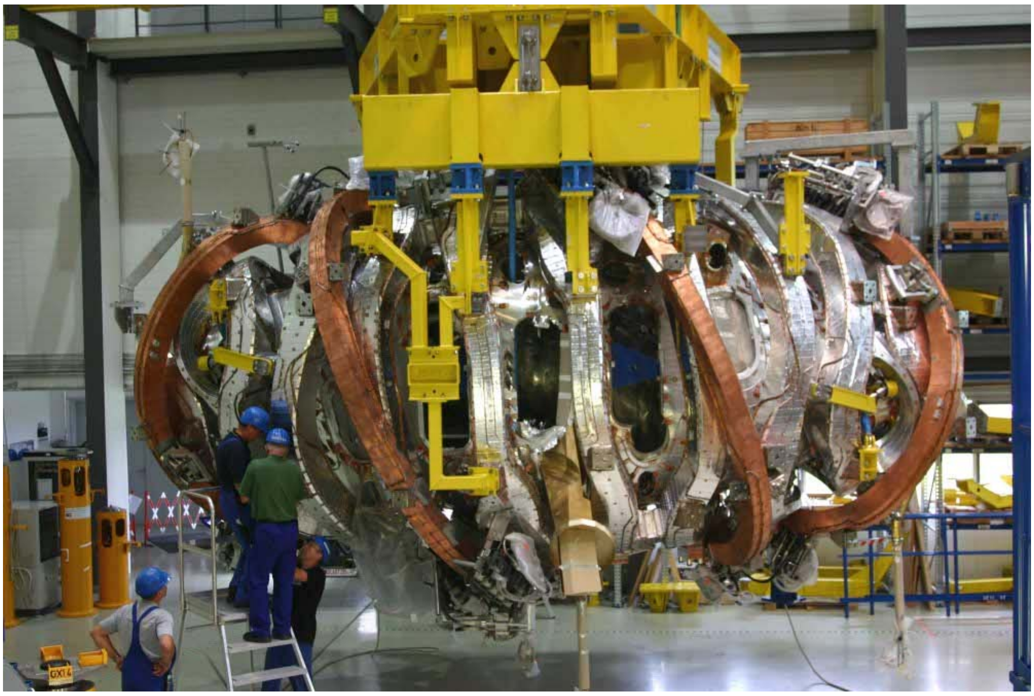

FIG. 5.Full magnet module attached to the transport frame for relocation to next assembly stand.

4.2. Vessels, ports and thermal insulation

At the inside of the outer vessel shells the thermal insulation and the thermal shield are being fastened. To avoid damage during the handling and assembly of the outer vessel shells are stiffened and reinforced by a suitable tool (cf. Fig. 2). Another task is the positioning and welding of three plasma vessel supports into every bottom shell.
For the assembly of the 254 ports the required equipment is manufactured in the industry at present and are available beginning of 2009. A port-assembly bridge spans three sides of the module. It carries a port assembly ramp, which enables the precise alignment of ports in six degrees of freedom. To be able to install ports also from the bottom side, a second port ramp is operated from the floor. Also the ports must be thermally insulated on site.

5. En route to steady state operation

The plan for commissioning and first operation of Wendelstein 7-X is shown schematically in the diagram Fig. 6. Assembly completion will be in mid 2014 (with more than one year contingency on the critical path).

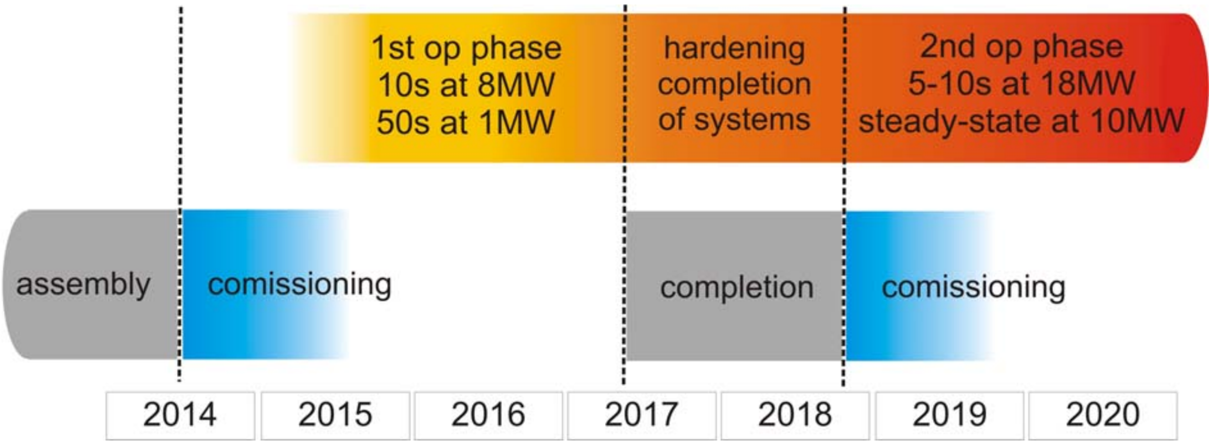

FIG. 6. Schematic diagram showing the first years after assembly of Wendelstein 7-X.

After the commissioning of the device (supply and control systems, vacuum, cryo, magnetic field) the first plasma operation is planed with 8MW ECRH heating power or 7MW NBI(H) power. During this first operation phase the discharge duration is limited to 5-10s, since the water-cooling of all in vessel components will be completed afterwards. In particular an inertially-cooled test divertor unit instead of the water-cooled steady-state divertor is installed in order to collect first experience with different plasma scenarios. The scientific program of the first operation phase is roughly described by the following key words:

- achievement of density control up to X2-cutoff point
- demonstration of good confinement properties
- achievement of impurity control
- development of optimum divertor scenarios with tolerable loads
- development of efficient X2-current drive for bootstrap current compensation
- exploitation of high density plasmas far beyond the Greenwald limit
- achievement of divertor high recycling operation
- first exploitation of O2-heating up to cutoff point
- first exploitation of efficient O2-current drive

The accomplishment of these goals and the experience collected with the device forms the basis for steady-state operation at power levels up to 10MW. For that, during the subsequent completion phase, all systems are completed and hardened for steady-state operation at high heating power, in particular the in-vessel components and the diagnostics. The test divertor unit is replaced by the steady-state divertor and all plasma facing components are connected to the water cooling circuits. In the second operation phase, long plasma discharges with the steady-state divertor are started and advanced plasma scenarios (e.g. the HDH-mode [5]) are systematically developed.

6. Summary and lessons learned

Wendelstein 7-X is a large, physics-optimized, superconducting stellarator in an advanced state of construction. The construction progress is now according to plan and the major milestones have been kept. To cope with the remaining technical risks, more than one year of contingency on the critical path is included in the planning.
Wendelstein 7-X is expected to be a major fusion research facility and a forerunner for high-power steady-state plasma operation. Furthermore, it has the mission to demonstrate the reactor potential of the quasi-isodynamic magnetic field concept. There are no indications for reduced device performance, and the planned scientific program should be fully possible without restrictions.
The construction of Wendelstein 7-X experienced a number of serious technical set-backs and considerable delays. After a complete re-organization of the project and a thorough revision of the plans, a robust schedule is now available with the end of device assembly in mid 2014. It must be kept in mind, however, that Wendelstein 7-X is a first-of-its-kind device an means a huge technological step from its smaller (normal conducting) predecessor device Wendelstein 7-AS [5]. Main lessons learned are the following:

1. Sufficient man-power especially in the engineering must be provided.
2. Sufficient technical know-how and workshop capacity must be provided.
3. Recruitment and training of young engineers must be a high priority task.
4. After a detailed design review the design of each major component must be frozen.
5. Design works must be done in a central office with a common documentation system.
6. For a functioning collision control the as-build model of all components is required.
7. A formal but active change and configuration management is mandatory.
8. A strong but pragmatic quality management is mandatory.
9. All major technologies must be tested and qualified before their application.
10. Integrated time and budget planning with suitable tools is indispensable.
11. Strict project structures and strict project management are mandatory.
12. Major project risks cannot be transferred to industry at reasonable costs.
13. Technical problems in the manufacturing must be mainly solved by the home team.

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