Wendelstein 7-X – a Technology Step towards Demo

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The Wendelstein 7-X stellarator, presently under construction in Greifswald, will be the first "fully-optimized" stellarator device which combines a quasi-symmetric magnetic field configuration with superconducting coils, a steady state exhaust concept, steady state heating at high power and a size sufficient to reach high $nT\tau$-values. W7-X has been optimized numerically by J. Nührenberg *et al.*, based on the concept of quasi-isodynamicity. Its key element is an optimized magnetic field configuration, generated by 50 non-planar superconducting coils. It is the mission of this project to demonstrate the reactor potential of the optimized stellarator line. Most of the components have been fabricated already and four out of ten half-modules of the magnet system have been assembled up to now. This paper presents an overview of the status of construction and a summary of the future developments.

Keywords: Wendelstein 7-X, optimized stellarator, construction, assembly

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1. Introduction

Wendelstein 7-X (W7-X), presently under construction in the IPP branch-institute in Greifswald, is a fully optimized stellarator. Its optimisation is based on the concept of quasi-isodynamicity [1].

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

W7-X will have to prove the properties predicted by the numerical optimization, i.e. confinement in the range of that observed in tokamaks of comparable size. Apart from this proof of the concept of numerically optimizing the stellarator magnetic configuration, a main goal of W7-X will be to demonstrate the suitability of optimized stellarators as a fusion power plant and to bring forward the technology towards "Demo." One key element that is still to be developed for a future fusion power plant, is steady state operation under reactor-relevant conditions, i.e. at high density and high power relevant to a a power plant and steady-state particle exhaust. To allow for steady-state operation (i.e. pulse lengths of 30 minutes - limited by the water cooling system), W7-X will apply a superconducting magnet system composed of 50 non-planar coils and 20 planar coils, an ECRH-system capable of delivering 10 MW for 30 minutes [2,3] and will also develop further the island divertor [4] and will address the plasma-wall interaction in long plasma pulses.

This paper will give an overview on the main components of W7-X and describe the status of device assembly.

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2. Main Components of W7-X

Figure 1 shows a schematic overview of the basic device. It is clearly visible, that the plasma has a pentagon-shape. The device is therefore set-up from five identical modules. Each of those, however, is made out of two flip-symmetric half-modules, so that in fact the device is composed of 10 almost identical half-modules.

2.1 Magnet system

The magnet system is made from 50 non-planar coils for the basic magnetic field and 20 planar coils to allow for a variation of the magnetic field configuration, a bus-bar system to connect these coils electrically with each other and with the power supplies (not visible in Fig. 1), a central support structure and a set of support elements fixing the

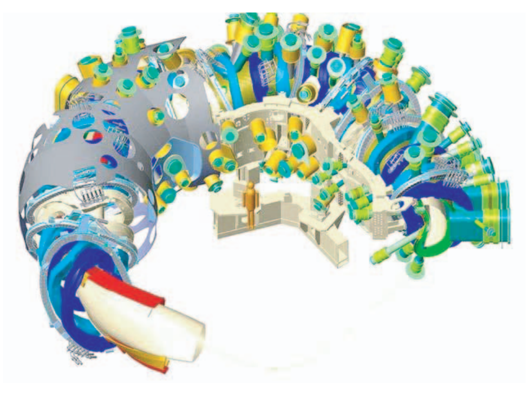

Fig. 1 Cutaway of a CAD drawing of W7-X showing the plasma and the divertor plates (lower left), the magnetic coils around the plasma vessel with inner support structure (upper right) and the Outer Vessel (upper left).

coils to the central ring and supporting them against each other. The total cold mass of this magnet system will be 432 tons. According to the symmetry described before, each half-module is equipped with 5 non-planar coils of a different type and two planar coils (again different types).

2.1.1 Superconducting coils

The 50 non-planar coils that comprise the centerpiece of the magnet system have been manufactured by a German-Italian consortium of BNG and ASG [5]. For each coil 6 lengths of superconductor are wound as a double-layer with 18 turns each, i.e. 108 windings per coil. Very stringent tolerances on the geometric dimensions of the winding packages of less than 3 mm had to be kept. This leaves a margin for assembly tolerances of about the same order to guarantee the quality of the magnetic flux surfaces.

The six superconductor lengths in one coil are connected in series through low resistance joints ($< 1\,\text{n}\Omega$ which are also used to introduce the liquid He for the cooling of the superconductor. Figure 2 shows the non-planar coil of type 4. The insulation in the header region, i.e. at the exit of the layers from the winding pack and around the interlayer joints has proven to be an especially difficult area requiring extensive rework. Paschen tests, i.e. high voltage tests at different pressure levels, have proven to be a very effective tool for testing the quality of this insulation [6] and for unveiling problematic areas like small voids, areas of pure, unfilled resin or insufficient insulation of quench detection wires.

As of now, all 50 coils have been delivered. 38 of these coils have been tested individually at cryogenic temperatures in full-current operation and have proven the expected properties [7]. These cryogenic tests are being performed for all coils at CEA in Saclay/France as part of the final acceptance test.

Fig. 2 Non-planar coil type 4 on a transport frame. Clearly visible are the Copper stripes on the coil casing and the cooling tubes. In the lower right part of the picture, the header area with the five interlayer joints and the two superconductor tail ends can be seen.

The 20 planar coils, supplied by Tesla in the UK, have casings that are made from two vertical rings and top and bottom plates bolted to them [8]. As of today, all coils have been delivered and 19 of them have already successfully completed the cryogenic tests in Saclay.

2.1.2 Bus-bar system and current leads

To connect the coils with each other (seven groups of 10 identical coils in series) and with the current leads (which lead to the power supplies at ambient temperature), a superconducting bus-bar system is required which is being designed and manufactured by the research centre Jülich (FZJ, Germany) [9]. The same conductor is used as for the coils and the routing is done in a bifilar way to reduce error fields from the bus-bar. The design of the bus-bar system has been finished and manufacturing has started. The first 48 conductors (i.e. conductors for two modules) have been delivered, together with the corresponding supports (holders and clamps).

The connection between the power supply lines outside the cryostat (i.e. at ambient temperature and pressure) and the bus-bar system inside the cryostat (i.e. at about 4 K during operation and under vacuum) requires 14 current leads that bridge the temperature and pressure transition. As the power supplies are located below the W7-X, these current leads are mounted in the bottom of the device and have the cold end at top, the warm end at the bottom and therefore require a special design. A design for these current leads, able to carry 20 kA each and using high temperature superconductor inserts, has been developed in collaboration with the research centre Karlsruhe, Germany (FZK). Development and manufacturing of these current leads is now under way at FZK [10].

2.1.3 Power supplies

The seven groups of superconducting coils are powered by seven power supplies manufactured by the Swiss company ABB. Each power supply delivers a direct current of up to 20 kA at a voltage of up to 30 V. This system has undergone the final acceptance tests and has proven that the output currents can be stabilized to the required accuracy of 2×10^{-3} [11]. The quench detection system, developed in co-operation with FZK, will consist of almost 400 quench detection units that check permanently the differential voltages between double-layers of all coils and between all sectors within the bus-bar system [12]. The prototype units have been tested successfully and series production will start soon.

2.2 Cooling system

The cooling of the cold components to cryogenic temperatures is provided by a He refrigerator plant with a cooling capacity equivalent to about 7 kW at 4.5 K [13]. Different consumers will be provided by this plant. The coils (casing and winding packs), coil support structure (see below), current leads, and the cryo vacuum pumps in the divertor are cooled with a forced flow of single phase helium. The cryostat thermal insulation shield is cooled with He at 60-80 K. For the shield of the cryo vacuum pumps, a two-phased flow of liquid nitrogen is foreseen as refrigerant.

All components of this helium plant have been installed. The tests for commissioning the plant are currently running.

The conceptual design of the cryo-piping has been finished and structural analyses have been performed [14]. At the moment, the final design which has to be adapted for each module individually due to the very tight space situation inside the cryostat, is being done and fabrication has started. The pipe system for the first module has been manufactured to about 75%.

2.3 Magnet support system

The 50 non-planar and the 20 planar coils will all be fixed to a central support ring, which is manufactured by ENSA in Spain. This structure is composed of 10 identical, welded segments which are bolted together to form a pentagon-shaped ring of 5 modules. Cast extensions for holding the coils are welded to this ring [15]. As the coils have to be kept in their precise position, also during cool down and operation, the half-modules of this central ring have to be machined to a high accuracy of a few tenth of a millimeter. The continuous refinement of structural calculations resulted in different modifications to the original design of the structure, thereby delaying the manufacturing. The first six segments of the support ring (see Fig. 3) have been delivered up to the end of 2008.

Ten cryo-supports will carry the support structure and provide a thermal barrier between the cold magnet system and the machine base. Fabrication of these cryo-supports is under way, their delivery is expected early in 2009.

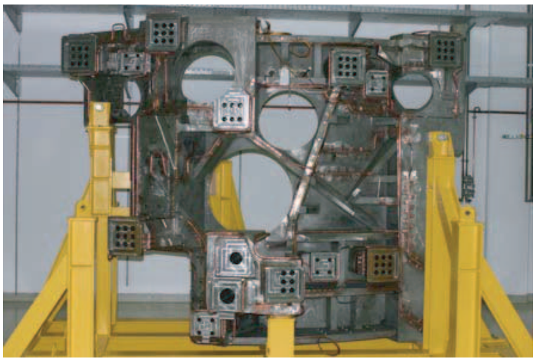

Fig. 3 First segment of the central support ring (1/10 of the full ring). Clearly visible are the cast extensions with the contact surfaces for fixing the coils. The circular holes in this structure are required for the ports on the inner side of the torus.

Each coil is fixed radially to the ring in two points, where the magnetic forces (up to 4 MN) and bending moments (up to 350 MNmm) have to be taken up. A bolted solution using long and slender Inconel bolts (which better absorb deformations) and sleeves to limit the loss of pre-load during cooling down to 4 K has been developed to keep the coils firmly in place [16].

Also in toroidal direction, the non-planar coils have to be supported against each other with a system that can take up the forces and moments and keep the positions of the coils to a high accuracy. Therefore, on the inner side of the coil ring, where the coils are very close to each other, so-called Narrow Support Elements (NSE, see [17]) and on the outboard side the so-called Lateral Support Elements (LSE) are foreseen. These LSE will be a rigid connection made of half-boxes which are welded between the neighboring coils. The crucial issue with this design is the proper control of welding shrinkage and distortion which is essential to comply with the magnet system assembly tolerances. An extensive test program has been carried out to optimize the layout and welding procedures for these elements.

The situation is different for the NSE because on the inboard side of the coils accessibility restrictions do not allow any welded or bolted solution. Based on refined FEM calculations which revealed that contact forces up to 1.5 MN and sliding distances of up to 5 mm with a tilting up to 1 degree have to be expected during magnet energization, a sliding pad solution has been selected. After an extensive test program, Al-bronze with a MoS_2 coating has been chosen as the material for thick, low friction pads which are fixed in a pad holder to one coil, sliding on the support block of the other coil. To validate the basic design and to identify the best pad coating, a wide test program has been undertaken, including full scale friction tests at room temperature and cryo-vacuum tests at 77 K to test the full scale mock-ups in a more representative environment. A design similar to the one for the NSE is used for the so-called Planar Support Elements (PSE) which support the planar coils against the non-planar coils.

2.4 Cryostat

The cryostat, providing the thermal insulation of the cold magnet system described before, consists of the plasma vessel, the outer vessel, the ports [18] and the thermal insulation of these components towards the cold mass.

The vacuum vessel of W7-X has been manufactured by the German company Deggendorfer Werft und Eisenbau (MAN DWE). A major issue in the design of this vacuum vessel was the optimization of its shape to allow for maximum space for the plasma and to simultaneously keep sufficient clearance to the coils. These requirements resulted in a tolerance of only ± 3 mm for the shape of the plasma vessel in the most critical regions. The full plasma vessel is made up from 200 rings that are connected by welding. Each ring is made of four segments that are precisely bent to the exact shape. Twenty of these rings form one half-module. Water pipes on the outer side of this vessel allow a bake-out at 150°C and temperature control during plasma operation. All ten sectors of the plasma vessel have been delivered before the end of 2005.

The outer vessel, also manufactured by MAN DWE, is produced in 5 modules; each of them is divided in two (upper and lower) half-shells to allow assembly of the magnet module (plasma vessel module with 14 coils, support structure and the corresponding bus-bars) inside the outer vessel module. The outer vessel will have about 524 openings for ports, supply lines, manholes and diagnostic feedthroughs. The first four modules have been finished (see Fig. 4), the last one will be finished in spring of 2009.

W7-X will be equipped with 254 ports of different shape and dimensions (up to $40 \times 100\,\mathrm{cm}^2$ rectangular ports) to allow access from the outside to the plasma vessel. 112 of these ports will be used for plasma diagnostics, 17 for heating systems, 25 for gas inlet and for pumping the vacuum vessel and 100 for supply of in-vessel components. All ports have been received from the Swiss company Romabau Gerinox.

Efficient operation of the superconducting coils requires very effective reduction of heat conduction as well as shielding of radiation from the room temperature components of the cryostat. The thermal insulation of W7-X (also manufactured and assembled by MAN DWE) is composed of two components, a multi-layer insulation of aluminized Kapton-foils (20 layers) and a rigid thermal shield. As the space limitations for this insulation between the vacuum vessel and the non-planar coils require again a tolerance of ± 2 mm, a novel technique has been developed. The thermal shield is now fabricated from glass-fiber panels with embedded Cu-meshes to improve heat transport within the panel. Cooling pipes on the outboard side of the panels q are connected to the Cu meshes through Cu-braids [19]. For each half-module of the vacuum vessel, eight panels of the shield with attached multi-layer insulation are fabricated. They are assembled on the plasma vessel in parallel with the threading of the coils. Recently, assembly of the thermal insulation in the outer vessel of the first module has started. For the outer vessel and the ports the shields are made from copper and brass.

Fig. 4 First module of the outer vessel during fabrication at Deggendorf.

2.5 In-vessel components

At the plasma edge, i.e. outside the closed flux surfaces, the magnetic configuration of W7-X forms a $m = 5$ island structure to be used as an island divertor to control the power and particle exhaust from W7-X [20]. According to the field structure described above, also the divertor will have a five-fold symmetry, i.e. it will be composed of 10 units, five on top and five on the bottom. The full system of the in-vessel components includes several plasma-facing elements as well as cryo pumps and correction coils to modify the extent and location of the islands on the target plates. This system has been designed for steady-state operation at the full ECRH-heating power of 10 MW and for 10 s pulses of 15 MW NBI heating power [3].

For the plasma-facing components three different areas have to be distinguished which require different technical solutions respectively. The divertor target (with a horizontal and a smaller vertical target plate) will experience high power fluxes of up to $10\,\mathrm{MW/m}^2$. The baffle shielding the neutrals in the target chamber versus the main plasma chamber, experiences lower stationary power fluxes of only up to $0.5\,\mathrm{MW/m}^2$. The wall protection, covering the rest of the plasma vessel surface, is subjected to neutral particles and plasma radiation and is designed for power fluxes of $0.2\,\mathrm{MW/m}^2$.

2.6 Diagnostics and control system

Steady state operation also poses new challenges for diagnostics. Continuous plasma heating in W7-X with 10 MW ECRH will result in thermal loads of 50-$100\,\mathrm{kW/m}^2$ from radiation onto all plasma-facing components and additional loads of up to $500\,\mathrm{kW/m}^2$ onto those components which are also exposed to convective losses. Spatially varying micro-wave stray radiation with power levels of 50-$200\,\mathrm{kW/m}^2$ can impose a large energy into the in-vessel components over the long discharge times and has to be avoided by proper material selection and careful shielding. Coating of windows and plasma-facing optical components results in gradually increasing transmission losses. Therefore in-situ cleaning as well as shielding of these components has to be considered. Extensive development effort is on going to adapt the diagnostics systems to these conditions [21].

Also the control system will face new challenges with discharge times up to 30 minutes. Such time scales require a complex and intelligent feedback-control scheme because parameters such as auxiliary heating or plasma density can not be programmed in a purely feed-forward way anymore. The control system, instead, has to be able to adjust the control variables in a flexible way during the discharge. On the other hand, such long discharge times allow to run several experiments in a single discharge. The control system foreseen for W7-X will be hierarchically structured. Each local component, such as coil power supplies, heating and cooling systems, diagnostics and so on, has its own Local Control System (LCS). For commissioning and tests, these LCS are operated autonomously. For the operation of W7-X, all these components will be controlled by the Central Control System (CCS), which coordinates the activities of the subordinated LCS [22, 23]. The safety system is independent and consists again of local units for each component and a central safety system controlling the safety of the full system. The central safety system provides interaction between components and the human interface and controls all interlocks.

This control system for W7-X is under development and a first prototype is currently operated on the small WEGA stellarator in Greifswald [24]. The further development of the W7-X control system will be based on the experiences from this prototype.

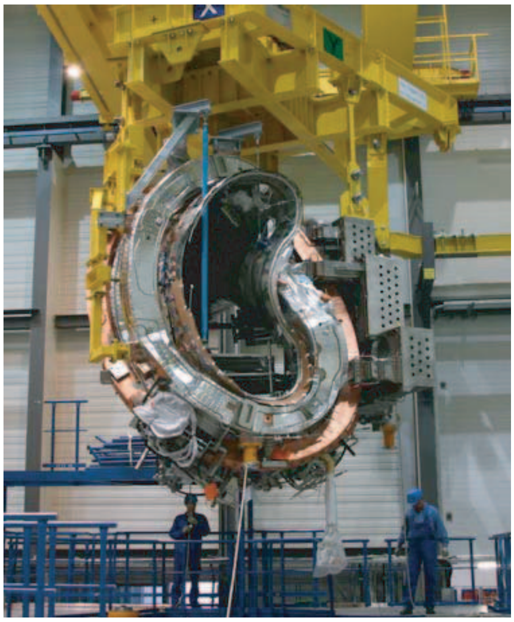

Fig. 5 First magnet half-module being transported to assembly rig II (February 2008). The central support ring with its step flange for connection of the two half-modules is visible on the right as well as the extensions for coil fixation.

3. Assembly of Wendelstein 7-X

3.1 Assembly sequence

Assembly of the stellarator comprises two major stages, i.e. pre-assembly of the five magnet modules and assembly of the torus. A detailed description of this sequence can be found in Ref. [25].

In the first step of the pre-assembly, which is performed roughly in parallel on two assembly rigs (Ia and Ib) for two half-modules, the seven coils are strung over the vacuum vessel which is covered with the thermal insulation. Then all coils are fixed to one segment of the central support ring and the inter-coil support elements are mounted (see Fig. 5). In the next step, on assembly rig II, the two corresponding half-modules are joined, i.e. the support ring segments are bolted and the plasma vessel half-modules are welded. Then the bus-bar holders are mounted and the conductors are fitted and cut to length. On assembly rig III, the first part of the cryo-pipes (for helium cooling of the coils and the support structure) is assembled, then the bus-bar system, including the bus-bar joints, and the second part of the cryo-pipes, thereby completing a magnet module.

Final assembly starts with the insertion of the magnet module into a lower shell module of the outer vessel (first equipped with the thermal insulation and with three plasma vessel supports per module) which is then closed with the upper shell. At this stage, the module is located at its final place on the machine base. Then the installation of the ports can start. After a final measurement of the magnet modules geometry and after final adjustment of their position, the modules are bolted and welded together to finally form a torus. As soon as two adjacent modules are connected, the last ports, i.e. those at the module separation plane, are inserted and then the current leads and the in-vessel components can be assembled.

After the completion of the torus, the peripheral components (heating structures, ex-vessel diagnostics, water-cooling and other media supplies) can be installed.

3.2 General assembly works

In parallel to these main steps of the device assembly, a large effort is required for the preparation of the components delivered from industry, mainly with regards to cleaning, instrumentation, and measuring and final rework of the outer geometry.

For all the assembly steps described before, the assembly technology had to be developed, including special tooling for the handling of the coils, for handling and stiffening of the outer vessel shells and for the assembly of ports and of in-vessel components. A very special task was the development of welding procedures because for welding of the Lateral Support Elements or for the connection of vessel modules, large weld seams (up to 25 mm thick) have to be performed while weld seam shrinking has to be kept to a minimum due to the very strict tolerances (in the order of a few mm) of the stellarator.

The small tolerances required for the geometry, especially of the magnet system, also requires an extensive measuring program, involving 3D measurement techniques like laser trackers, photogrammetry and laser scanning [26]. Geometry control is an essential task in this project, as W7-X is a very complex but also compact device with very narrow installation space for all its components. Clearance of all these components during cooling down and especially under magnetic loads has to be assured, but is difficult to reach as the device is very compact and the distances in many cases are not far beyond the tolerances. Therefore an extensive effort has been put into measuring the as-built geometry of the major components and into the collision control of these components under the different load conditions. This process already enters into the design of components like the cryo-piping or the thermal insulation of outer vessel and ports, often requiring several iterations or – as mentioned above – the rework on components ready for assembly, like for coil casings or ports [27].

3.3 Status of assembly

At present, three out of the five modules are in the assembly process. On the first of these modules, which is presently on assembly rig III, the first lots of the cryo-pipes are being mounted. Due to the narrow installation space, mentioned above, design of these pipes requires several iteration cycles of design and collision control, making this process even more time-consuming than expected. Figure 6 illustrates the narrow assembly space with a CAD-model of the central support ring with the bus-bars and the cryo-pipes. The second module on assembly rig II and the third one (still in two half-modules on rigs Ia and Ib) are assembled on a routine basis.

In late spring of 2009 the first module will be put into the lower shell of the outer vessel and in fall of 2009, assembly of the first ports is scheduled to start.

There are still many assembly steps ahead, which have been developed, but have not yet been performed. Therefore the schedule bears still some uncertainty for the technical risks, especially in these new processes. With these considerations in mind, a full review of the assembly process has been performed in 2007 which resulted in an integrated assembly schedule incorporating several measures

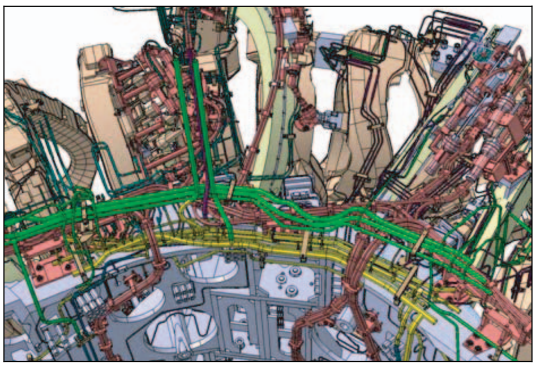

Fig. 6 CAD-view of the central support ring with some coils and bus-bars (brown) and cryo-pipes (yellow, green and black), illustrating the very tight assembly space inside the cryostat.

to minimize technical and schedule risks, e.g. the number of ports was reduced from 299 to 245 additional assembly equipment will be used to enhance the parallelization of assembly work and many assembly steps will be brought forward into the component preparation.

Another important decision was that, for the first operation phase, the steady state divertor described above will not yet be installed. Instead, a Test Divertor Unit (TDU) with inertially cooled target plates will be installed [4]. All other in-vessel components described above, will be installed from the beginning, but in the first operation phase will not be water-cooled.

Based on a risk assessment of all assembly steps, time buffers for the technical risk were included in the schedule, summing up to more than a year on the critical path. Also the funding required for these times was included in the projects planning.

4. Summary

While the timely delivery of the super-conducting coils for W7-X is no longer critical, other components like the cryo-piping, parts of the bus-bar system, thermal insulation of outer vessel and ports, parts of the in-vessel components and the current leads (feedthroughs) still require stringent attention as their delivery might become time-critical. The project has implemented counter measures to decrease the schedule risks.

Assembly at present runs according to the schedule planned in 2007 and the first milestones have been kept. The current delays in design, fabrication and assembly of the cryo-pipes can be countered by some reorganization of other assembly steps, but the assembly schedule requires strict attention and continuous consideration.

As there are still some assembly processes to be developed in further detail (assembly of some special ports and of some in-vessel components), it has to be considered that at least some of the time buffers mentioned above, will have to be used. But still the project schedule foresees the start of commissioning of Wendelstein 7-X in May 2014.

With the construction of Wendelstein 7-X major technological steps towards a Demo plant are done in several areas like e.g. design and fabrication of a large modular coil system, the development of a steady state high power divertor, (20 MW for 30 minutes), a steady state ECRH-system (10 MW for 30 minutes). Therefore, the experiences gained with Wendelstein 7-X will be a major base for further technological developments towards Demo.

Wendelstein 7-X, clearly, has not been optimised with respect to the engineering solutions, which is a common feature for a first-of-a-kind device. Future stellarator reactor studies, however, will have to combine physics and engineering optimization in a more rigorous way [28].

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