Overview of the construction and scientific objectives of the Wendelstein 7-X stellarator

H.-S. Bosch for the Wendelstein 7-X Team 1)

1) Max-Planck Institut für Plasmaphysik, Euratom Association, Greifswald, Germany

E-mail contact of main author: Bosch@ipp.mpg.de

Abstract. Wendelstein 7-X, the first numerically optimized stellarator, is presently under construction and completion of assembly is scheduled for summer of 2014. This paper describes the design and the present construction status of Wendelstein 7-X. Subsequently we describe the experimental capabilities foreseen for the initial operation phase and the framework for the commissioning phase and a research programme for the first operational phase.

1. Introduction

The Wendelstein 7-X stellarator, presently under construction in Greifswald, will be the first "fully-optimized" stellarator device [1] which combines a quasi-isodynamic magnetic field configuration sustained by superconducting coils with a steady-state divertor, steady-state heating at high power, and a size which is sufficient to reach reactor-relevant $nT\tau$-values. The main objective of the project is to demonstrate the integrated reactor potential of the optimized stellarator line. Steady-state operation is an intrinsic feature of stellarators since the vacuum magnetic field already provides plasma confinement. To prove the perspective for a stellarator reactor, however, steady-state operation has to be demonstrated in an integrated operation scenario at high heating power and densities/temperatures relevant for a fusion reactor, simultaneously combined with sufficient thermal and fast ion confinement and a divertor concept that provides reliable power and particle exhaust. Such a reactor relevant steady-state operation has not yet been demonstrated in a stellarator and therefore represents the major scientific goal of Wendelstein 7-X [2].

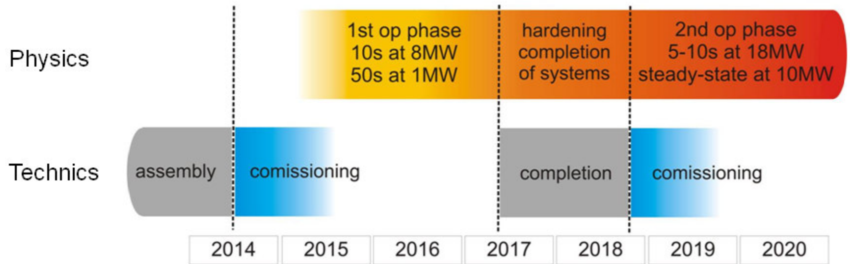

Fig. 1 Staged approach for the start-up of Wendelstein 7-X. In the 1st operation phase, basic stellarator properties will be investigated and high density scenarios will be developed. After completion of the device, steady state operation will be explored.

For the scientific exploitation of Wendelstein 7-X, a staged approach has been developed, shown in Fig. 1 [3]. After completion of the Wendelstein 7-X construction, scheduled for summer 2014, a commissioning phase of about one year is foreseen. In the first operation phase, starting in summer 2015, basic stellarator properties and operation scenarios are investigated still with short plasma discharges (5-10 s duration). The goal of this initial phase is the development of a controlled, integrated high-density scenario with edge conditions suitable for steady-state divertor operation [3], which will later be the starting point for exploring high-power steady-state operation in a second phase. During this phase of about two years, the technical requirements for in-vessel components are much less challenging than for steady-state operation. Therefore, a temporary test divertor unit (TDU) with inertially cooled target plates will be installed and also the wall protection elements will not be completely water-cooled.

After the first operation phase, a shut-down is foreseen in which the device will be upgraded for steady-state operation. The TDU will be replaced with a water-cooled steady-state divertor, the divertor cryo pumps will be installed, and the water-cooling lines will be completed. Plasma heating and diagnostics will be extended. After completion of the device, the physics programme will be extended. In the second operation phase, the physics and the technological issues of steady-state fusion device operation will be intensively addressed.

2. Construction of Wendelstein 7-X

During the last two years, construction of Wendelstein 7-X has entered a new phase, as most of the major components of the device have been delivered [4]. The manufacturing of the 70 superconducting coils has been completed with the successful tests of all coils under cryogenic conditions. The power supplies for these coils and the coil protection system have been installed and commissioned. Fabrication of the bus-bars (to connect the coils with each other and with their power supplies) has been completed recently. The current leads to connect the power supplies (at room temperature and ambient pressure) with the coils and their bus-bars inside the cryostat (at cryogenic temperature and under vacuum) have been developed by the Karlsruhe Institute of Technology [5] and series fabrication is about to start. The cryo plant [6] is presently being commissioned.
All large cryostat components (plasma vessel, ports, outer vessel) have been delivered and design and manufacturing of the in-vessel components is progressing according to plan.

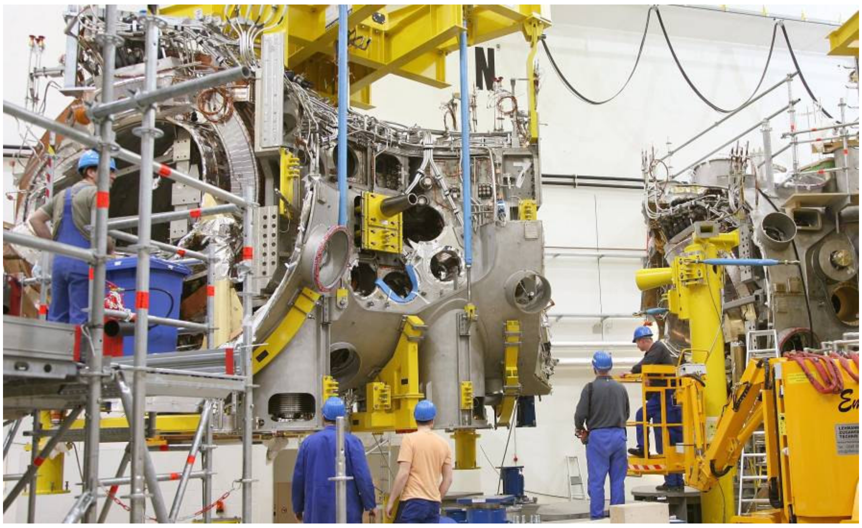

Fig. 2 View into the W7-X torus hall (May 2010). On the right, the first magnet module is positioned on the machine base within the outer vessel (cryostat) module. In the center, the second magnet module in the lower shell of the cryostat is just being trans-ferred onto the machine base.
As of now, the third module has been added also.

With the main components ready for assembly, the main objective of the project now is the device assembly. The assembly strategy foresees first the assembly of the five identical magnet modules in several steps [7]. These steps are performed on different assembly rigs and the modules can be assembled in parallel. The finished magnet modules are then assembled in the lower shell of the cryostat module and are positioned on the machine base. Here the upper shell of the cryostat module is added and both shells are welded together. Then about 50 ports per module (together with their thermal insulation) are installed between plasma vessel and outer vessel to complete a stellarator module. Finally, the five modules will be connected to form a torus and the peripheral components (electrical and heating/cooling installations, heating and diagnostics systems) will be completed. In the first module all 45 ports have been installed and final welding is about to start. Port installation in the second module has just started and also the third module has already been positioned on the machine base, awaiting the upper shell of the cryostat. On the last two magnet modules, assembly of the bus-bars and the cryo-piping is under way.

Until now most assembly steps have been performed already at least once and – in this process – have been optimized. This experience allows for a rather stable assembly schedule, compensating delays in areas where the effort has been underestimated.
There are, however, three major work packages that are presently being developed, but still lack practical experience, namely the connection of modules, assembly of the in vessel components and of the peripheral systems. These steps, especially the first two, will be verified by mock-up tests as far as possible. The schedule for Wendelstein 7-X assembly as derived from the technological planning, foresees the conclusion of assembly and the start of commissioning for the summer of 2014.

3. Wendelstein 7-X configuration for the first operation phase

After the commissioning of the device [3], a first operation with short plasma pulses at 8MW heating power is scheduled to investigate the numerical stellarator optimisation of Wendelstein 7-X and to develop an integrated steady-state operation scenario which is compatible with the island divertor concept.

The main tool for the development of high-power steady-state scenarios in this phase is an inertially cooled test divertor (TDU) [8]. It has the same geometric features as the steady state high-heat-flux (HHF) divertor which will be installed after this operation phase. This actively cooled divertor is designed for stationary heat fluxes of up to 10 MW/m^2 on the target elements [9]. All remaining in-vessel components (all baffle and wall protection elements) will be installed from the beginning, together with their respective cooling circuits. However, the piping in the torus hall and the connection to the water cooling system will be completed only for the second operation phase, as a cooling for the short plasma pulses is not necessary. Only for some elements near the ECRH antennae and the NBI ports and for some in-vessel diagnostics, water cooling will be provided from the beginning. Also the divertor cryo pumps, located behind the divertor targets, will be installed after the first operation phase, as their additional pumping capability is required only for steady-state operations.

The main tool for heating and current drive will be a long-pulse electron-cyclotron resonance heating (ECRH) system at 140 GHz with 10 gyrotrons, capable of delivering up to 10 MW over 30 minutes [10]. The prototypes and first series gyrotrons have achieved a power level of more than 900 kW per unit taking the transmission line losses into account. However, due to problems during series production, a new electron beam tunnel has been developed that promises reliable high power for the 1MW gyrotrons [11].

Plasma operation with an ECRH system at 140 GHz requires a magnetic field of 2.5 T in the plasma center to allow absorption of the second harmonic X-mode. Plasma start-up with X-waves at the second harmonic is a well-proven and reliable method [12]. The plasma is optically thick for these waves, i.e. absorption is good and stray radiation should not be a major problem. The cut-off density is $1.25 \cdot 10^{20}$ m^{-3}, which is no limitation for plasma start-up. Due to limitations of the high-voltage power supply, the ECRH-system in this phase can be operated with 8 out of the 10 gyrotrons, allowing for a total heating power of 8 MW. Injection of the ECRH waves is performed with four beam launchers, each being equipped with three individually steerable front mirrors. Their steering range is -15^o < φ_{tor} +35^o and -25^o < υ_{pol} < +25^o with a steering velocity of 25 ^{o}/s. Cooled reflector tiles will be assembled on high field side to reflect the radiation not absorbed during the first plasma transit. Plasma operation is also possible, if required, at lower magnetic field. The gyrotrons can be tuned to 104 GHz and X2-heating is possible at 1.85 T with a density limit of $6.8\cdot10^{19}$ m^{-3}. The output power of the ECRH system in this mode is reduced by about a factor of two.

The second heating system foreseen for the first operational phase of Wendelstein 7-X is a neutral beam injection (NBI) system, based on the NBI-system for ASDEX Upgrade [13]. It consists of two beam boxes, each one equipped with two plasma sources. The acceleration voltage will be 55 keV for hydrogen and 70 keV for deuterium. This system will provide a heating power of 7 MW with hydrogen atoms or 10 MW with deuterium. In order to minimize activation of the TDU before its replacement, however, operation of NBI in the first operation phase will be limited to hydrogen beams. The two beam-lines inject toroidally symmetric, with an injection angle of $\pm$7.44 degree measured against the radial direction.

A high-power ICRF system for plasma heating and fast ion physics studies is planned only for the second operation phase of Wendelstein 7-X. For the first phase a low power ICRF system is foreseen for plasma start-up and vessel conditioning with magnetic field applied.

The diagnostic system needs dedicated developments for steady state operation [14]. This includes specific issues, such as vibration compensation of interferometers or long pulse stability of electronic integrators, contamination of mirrors and windows by plasma residues, thermal heat loads from the plasma, and ECRH stray radiation. For the first operation phase, a basic set of 32 diagnostics is foreseen to be available. Although in this phase the requirements with regards to steady-state operation are somewhat relaxed, in most cases the final system - capable of steady-state operation - will be installed from the beginning.

To ensure the integrity of the Wendelstein 7-X in-vessel components and for the assessment of steady-state operation strategies, complete observation of the plasma-facing surfaces is required. This will be provided by ten video cameras with toroidal viewing lines and an imaging system that covers all ten divertor units in the infrared (IR) as well as the visible spectral range. All these systems will be integrated into the device safety control system. The 10 IR/visible divertor observation systems will be used to investigate whether particle drifts, field asymmetries and actual strike line widths limit the maximum permissible heating power and whether additional measures have to be taken to avoid an overload of the divertor targets.

For the MHD equilibrium, a full set of magnetic diagnostics (Rogowski coils, saddle loops and diamagnetic loops) will be available. For magnetic fluctuation measurements, a total of 224 Mirnov coils are being installed. These systems are complemented by a 400-channel soft X-ray multi-camera tomography system (XMCTS) with a spatial resolution of 3 cm and 1 μs time resolution, respectively.

To gain information on the impurity species and concentrations, a VUV spectrometer system will be available. It consists of four instruments covering the range from 2.5 to 150 nm. It has already been calibrated and extensively tested on the TEXTOR tokamak at the Research Center Jülich (Germany). This system will be complemented by a high optical throughput, fast time resolution CO-monitor (fixed wavelength, crystal based) and a pulse height analysis (PHA) system. For impurity transport and impurity confinement time measurements, initially a fast gas valve and in the second year of operation a laser blow-off system will be used in combination with the XMCTS and multi-foil X-ray spectrometer (MFS) system.

For the plasma core, a 20 channel Thomson scattering system with a spatial resolution of 2.5 cm and 20 ms time resolution will provide T_e- and n_e-profiles. This measurement will be accompanied by a single channel two-color interferometer $\langle n_e \rangle$-measurement along the Thomson scattering laser beam, using a CO and a CO_2 laser, allowing also for cross calibration. Furthermore a multi-channel dispersion interferometer system will gradually be built up from initially four to eleven channels. For fast (1μs) T_e-profile measurements a 36 channel ECE system with 1-2 cm resolution and the 6-12 channel MFS system will also be available. A dedicated diagnostic neutral beam will be available for active charge exchange recombination spectroscopy (CXRS) and for active neutral particle analysis (three analysers). Together they will provide measurements of ion temperature, rotation velocity, impurity density and radial electric field profiles as well as the energy distribution and slowing down function of fast beam ions. Z_{eff}-profiles will be provided by local CXRS measurements and derived from line of sight averaged Bremstrahlungs measurements as well as from passive soft X-ray profile measurements. Two bolometer camera systems will allow the determination of total radiation profiles by tomographic reconstruction.

For divertor physics investigations, two flush mounted Langmuir probe arrays have been integrated into the divertor targets of the upper and lower divertor. Furthermore visible spectroscopy arrays covering the region between target and separatrix in combination with vertical views onto the target cross section will give information on the position of the ionisation front, degree of detachment, line-of-sight averaged divertor plasma density and temperature profiles during detachment. More local measurements are possible in combination with the target-integrated thermal helium-beam array at lower densities and according to our latest study also at high density, low temperature detached plasmas [14]. 20 ASDEX type neutral pressure gauges distributed around the device will give information on recycling, pumping efficiency and neutral compression ratio in the divertor.

4. Commissioning and first physics operation phase of Wendelstein 7-X

After completion of the Wendelstein 7-X construction, a commissioning phase will follow. Local commissioning of all technical components (e.g. magnet system including power supplies, cryo system, diagnostic and heating systems and the control system), including their instrumentation and local control, has to be performed in parallel to the final stages of the assembly such that these systems are ready for the main part of the commissioning phase in 2014. This has three major work packages which have to be performed in series:

1. Vacuum operation, i.e. provision of ultra-high vacuum conditions in the plasma vessel and high vacuum conditions in the outer vessel: This involves confirmation of leak tightness of the plasma vessel, the outer vessel, water pipes and pipes for cryogenic helium, commissioning of the plasma vessel and outer vessel vacuum systems, of the plasma vessel conditioning systems and of the plasma vessel and in-vessel component cooling circuits which will also be used for baking at 150 °C. Conditioning without magnetic field will be done by glow discharge cleaning. For conditioning in the presence of a magnetic field, a dedicated RF-discharge system is foreseen.

2. Cryo operation, i.e., commissioning of the He-distribution system and cool-down of the magnet system: While the cryo plant will be commissioned separately in a stand-alone mode, the cryo-piping can be tested only during this phase with the cryostat being evacuated. It has to be confirmed that the cooling down of both the magnet system and the thermal shield to operational temperatures can be reached with the available cooling power. This includes adjustment of the helium flow in the parallel circuits and confirmation of leak tightness of the cold cooling pipes. The heat balance has to be checked in order to ensure that there are no thermal leaks or thermal shorts. A thorough configuration control, accounting for cool-down shrinkage and movements of the magnet system under load, was performed during design and device assembly [15]. This consequent configuration control is necessary to avoid thermal shorts due to a contact of 4K magnet components with the 60 K thermal shield.

3. Commissioning of the magnet system: After cooling down, i.e. when the coils are superconducting, operation of the coils can be started only after proper functioning of the quench detection and coil protection systems has been shown. Possible critical issues are the movement of the magnet system under the electromagnetic forces and potentially high mechanical loads on the various support structures. Therefore the coil currents will be increased only step-by-step towards their nominal values for 2.5 T operation. Wendelstein 7-X will be equipped with a large set of strain gauges, distance and contact sensors. Movements and mechanical stresses within the magnet system are continuously monitored with this instrumentation and the data measured during cool down and energization will be compared with results from FE-modelling [16]. Commissioning of the normal conducting in-vessel control coils also has to be completed at this stage. The commissioning of the magnet system will be completed with the measurement of the magnetic flux surfaces at full magnetic field [17]. Since the deformation of the coil system depends on the coil currents, however, the measurements of the flux surfaces will be performed in parallel to the increase of the coil currents to check the behaviour of the magnetic coil system with increasing electro-mechanical loads.

These three work packages will be performed in series and a approximate planning foresees a duration of about one year before the commissioning can be finalized with three important milestones, i.e. creation of the first plasma, extension of plasma duration to about 1s and a first check of the symmetry of the stellarator plasma at low heating power.

The aim of the W7-X is the development of *reactor-relevant* quasi-stationary discharge scenarios to prove the reactor relevance of the concept. This mission makes an *integrated physics concept* mandatory. In particular, this means the development of high-performance discharges (i.e. high $nT_i\tau_E$) integrating

1) Sufficient fast ion confinement
2) Control of magnetic field configuration (low bootstrap and Pfirsch-Schlüter currents) to achieve a stable resonant divertor configuration also at high beta
3) Divertor operation for density and impurity control

The first operation phase of Wendelstein 7-X will concentrate on the investigation of the basic stellarator properties combined with the verification of the optimisation criteria and the development of the integrated, controlled high-density scenario described above. Therefore, the research programme drafted for the first operational phase requires several steps [3]:

1) Density control investigations: The first investigations will concentrate on low-density, low-power ECRH discharges. The main topics of these experiments are 1) the symmetry of power load on targets for the different magnetic configurations, 2) the power load on baffles and wall, 3) tests of the safety diagnostics for interlocks, and 4) tests of profile diagnostics and online data evaluation.
2) X2-heating up to high densities: In the second step, the density and the ECRH power (in X2-mode) at full magnetic field, 2.5 T, will be increased up to the cut-off density of about $1.25 \cdot 10^{20}$ m^{-3}.
3) Confinement properties: This will allow for investigations of the confinement properties and a verification of some of the optimization topics, namely
   1. minimised Shafranov shift and stiff equilibrium
   2. minimised neoclassical transport
   3. minimised bootstrap current.

   This thorough check of stellarator optimization is performed by using the flexibility of the W7-X magnet system which allows for variations of neoclassical confinement properties as described by the effective helical ripple ε_{eff} [3].
4) Impurity control: Another important issue for achieving long pulse lengths at reactor relevant densities and heating power is the limitation of the impurity content in the plasma core to avoid the radiation collapse of the plasma. In order to limit the production of heavy impurity ions due to enhanced plasma-wall interaction, all heavily loaded in-vessel components (divertor, heat shields at positions with small plasma-wall distance, etc.) are shielded with carbon elements.
5) Tolerable divertor load scenarios: The most important issue here is an understanding and the control of the power load on the ten divertor modules. Only with an equally distributed power load it will be possible to use the full heating power in steady-state discharges. An asymmetry in the divertor load distribution could arise from magnetic field errors due to a misalignement of the 50 modular field coils beyond the very tight assembly tolerances.
6) X2-current drive for edge iota tuning: In order to provide the island structure forming the basis of the divertor configuration in Wendelstein 7-X, the value of the edge rotational transform ι at the plasma boundary has to be kept close to unity. As in some configurations the bootstrap current in the plasma could become large enough to modify the ι-profile, a control of the edge ι could become necessary. Therefore ECCD will be used for residual bootstrap current compensation and rotational transform control on L/R time scales (~ 30s).
7) Dense plasmas and divertor high-recycling regime: High density operation is a key issue for any fusion reactor, as fusion power density scales proportional to n^2, but also due to the favourable properties for high power divertor scenarios. Therefore the development of an operation regime like the HDH-mode [18] on Wendelstein 7-X will be an important research issue with respect to the preparation of steady-state operation. Neutral beam heating will be the main tool for these studies.
8) O2-heating and cut-off: For densities above $1.25 \cdot 10^{20}$ m^{-3}, i.e. when ECRH with X2-mode is in the cut-off, another heating method is required to extend the high density regime discussed before to a steady-state regime. To operate at such high densities, plasma scenarios with ECRH second harmonic O-mode heating (O2) have to be developed up to the O2 cut-off of $n_e = 2.4 \cdot 10^{20}$ m^{-3}.

5. Summary

Construction of the optimised Wendelstein 7- X stellarator is progressing well and commissioning of the device is scheduled to start in summer 2014. In a first operational phasefrom 2015 to 2017, the device will operate with inertially cooled in-vessel components, an initial set of diagnostics and plasma heating with 8 MW of ECRH and 10 MW of NBI. In this phase, the investigation of the optimization criteria will be started and plasma scenarios will be developed to prepare steady-state operation at high heating power. After a shut-down, when the device will be equipped with a steady-state high heat flux divertor, steady state plasmas will be explored. Then also the heating power will be sufficient to approach beta-values required to investigate improved fast ion confinement. A framework for a research programme for the first operational phase has been set up and will be further developed.

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