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Technical Aspects of Steady State Operation of WENDELSTEIN 7-X

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Abstract

The technical aspects of steady state operation of the W7-X stellarator are outlined. For cw-operation superconducting coils are necessary which are thermally insulated by a cryostat. The ECRH system of W7-X consists of ten gyrotrons with a cw-power of 1 MW each. ICRH and NBI are used in pulsed mode but can be upgraded for longer pulses. The control system allows a flexible use of the discharges. Diagnostics and data acquisition will handle the data with parallel computation and data reduction before storing. 48 MW of electrical power will be supplied from the mains which can be upgraded to 91 MW. The power supply for the heating is based on pulse step modulators with 3.3 MW cw- or 6.5 MW pulsed-power. The magnets are fed by 20 kA, 30 V modules with a fast protection system. The refrigerator is designed for 3.5 kW at 4 K. Large water reservoirs allow a pulse length of 30 min at full power.

Keywords:

WENDELSTEIN 7-X, steady state operation, magnet system, cryostat, plasma facing components, ECRH, ICRH, NBI, control and data acquisition, power supply, cooling

1. Introduction

The WENDELSTEIN 7-X stellarator (W7-X) is the next step device in the stellarator line of IPP Garching and is being built in the new branch of IPP at Greifswald. Start of operation is scheduled for 2006.

A schematic view of W7-X is shown in Fig. 1, the main parameters are given in Table 1. The physics background and objectives as well as the technical challenges of W7-X have been described in a number of publications (e.g. [1], [2] and references therein). In this paper, technical aspects of the different components of W7-X proper, the heating systems, the diagnostic and data acquisition as well as the periphery of the experiment will be described with emphasis on steady state aspects. Physics issues which mainly concern energy and particle handling together with plasma wall interaction will not be discussed.

Table 1: Main Parameters of W7-X

Mean major radius	5.5 m
Mean minor radius	0.53 m
Magnetic field on the plasma axis	3.0 T
Magnetic field on the conductor	6.7 T
Conductor current	18.2 kA
Temperature of the magnet system	3.8 K
Stored magnetic energy	610 MJ

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2. Components of W7-X and Steady State Aspects

W7-X is a **HELI**cal **A**dvanced **S**tellarator (HELIAS) with strongly varying plasma cross section, 5 field periods and low shear. The main components are the magnet system, the cryostat and the invessel components.

2.1 The Magnet System

A detailed description of the magnet system is given in [3]. It comprises 50 non-planar and 20 planar large magnet coils arranged in fivefold symmetry. For steady state operation these coils have to be superconducting. The conductor is a cable-in-conduit-conductor composed of 243 copper stabilised NbTi strands and enveloped by an aluminium alloy jacket. With this conductor the individual winding packages are built up, consisting of 6 or 3 double layers. For mechanical stability, each winding package is encapsulated by a stainless steel housing. The coils are cooled by a flow of supercritical helium inside the conductor (37 % void fraction) and through the cooling loops attached to each coil casing. The coil system, including the rigid support structure to handle the Lorentz forces of up to 3.6 MN per coil, has a weight of appr. 400 t. Cool down is expected to last two weeks and is foreseen only once a year.

To test the concepts of winding, insulation, embedding and electrical/mechanical stability a full-size DEMO-coil was built. This coil was tested successfully at Forschungszentrum Karlsruhe in the TOSKA facility. The results are:

- A critical current of 19.2 kA at a magnetic field of 6.8 T and a temperature of appr. 5 K, as predicted from single strand measurements.
- A completely elastic behaviour up to 114 % of the nominal mechanical force.
- A quench characteristic in agreement with the expectation.

Based on these results, the manufacture of the 70 coils has been released.

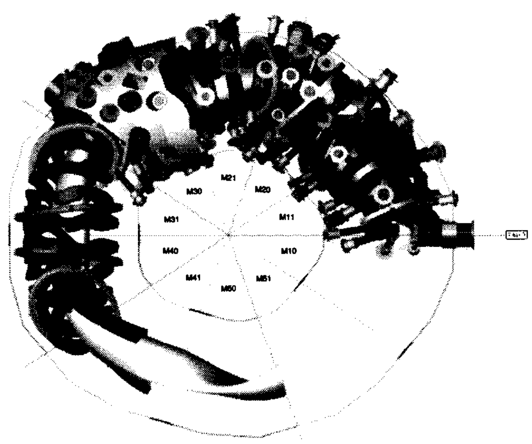

Fig. 1 Schematic view of W7-X

2.2 The Cryostat

The cryostat consists of:

- The plasma vessel, which follows the optimised shape of the plasma. It provides the UHV-conditions for the plasma operation and space and mechanical support for the in vessel components.
- The thermal insulation based on radiation shields, cooled to about 70 K, super insulation and vacuum.
- The 309 ports of sizes between 100 mm diameter and 1000×400 mm^2 cross-section for plasma diagnostic, heating, vacuum pumping and cooling water supply of the invessel components.
- The support of the cold mass.
- The outer vacuum vessel which encloses the whole device.

The main influence of the cryostat on steady state aspects are the thermal losses due to radiation and conduction. The following values have to be obtained:

- Thermal load less than 6 W/m^2 at 80 K and 0.1 W/m^2 at 4 K.
- A base vacuum of better than 10^{-6} mbar to have negligible gas conduction losses.
- Thermal conduction losses through the support of the cold mass (10 poles made of Fibre Epoxy) of less than 5 W at 4 K.

To test the concept of the cryostat and to gain experience for its manufacture and assembly, a full-size DEMO-cryostat was built, which represents 1/8 sector of W7-X and resembles all the features of W7-X except the coils which are dummies. This cryostat is presently under test at Garching.

2.3 The In-Vessel Components

A detailed description of the in-vessel components, especially of the plasma facing components (PFC) is given in [4]. Due to the steady state conditions at high heat loads and the 3D topology of W7-X, special solutions have to be developed for the divertor (target plates, control coils, baffles and cryopumps) and for the first wall. The PFC of both elements are designed to handle a cw-power of 10 MW each, with the total power not exceeding 15 MW.

Ten divertor units are installed in W7-X, i.e. two units per period. Each unit consists of two smooth sets of target plates and baffles, four cryopumps, a control coil and in addition a mechanical pumping system located outside of the device.

The target plates are designed to withstand a heat flux up to 10 MW/m^2 with a critical heat flux of 25 MW/m^2. One divertor unit consists of appr. 130 target elements, which span a 3D shaped area of 2.2 m^2. The single target elements are standardised with a width of 55 mm and a length between 270–500 mm. Flat Carbon Fibre Composite (CFC) tiles will be brazed or welded on a cooling structure which will consist of a copper or a molybdenum alloy. The thickness of the CFC (6–10 mm) is determined by the temperature limit set at the surface of 1000°C, the thermal conductivity of the CFC, the material of the cooling structure and the geometry of the cooling channels. For the envisaged operation of W7-X, erosion will not limit the lifetime of the invessel components. The development of a divertor system for the next generation with steady state operation is one of the main objectives of W7-X. The target plates will be actively cooled by pressurised water flow. The cooling system can provide a mass flow of 3000 m^3/h at a pressure drop of 14 bar. To suppress boiling due to the high wall temperatures of the cooling channels a static pressure of 10 bar will be applied.

The main purpose of the control coils is the correction of error fields and the modification of the plasma boundary. If the power deposition will become critical for cw-operation, they can be used to distribute the power to the target plates on a larger surface by sweeping the deposition area with a frequency of up to 20 Hz. This will reduce the time averaged power density without producing cyclic stresses. The time constants of the target elements are in the order of 3 s. The deposition area can be enlarged by a factor of two.

The baffle elements, covering 3 m^2 per divertor unit, are designed to withstand a power density of less than 0.5 MW/m^2. Two concepts are being studied and prototypes are manufactured for testing: Stainless steel quilted panels with surface layers of B_4C (low Z-material, reduced gas inventory, controlled surface temperature and gas release during long pulse operation) or clamped C tiles on water cooled support structures. The same concepts as for the baffles will be used for the first wall elements, which have to cover an area of 100 m^2 and will be designed for a power density of less than 0.2 MW/m^2. The temperature of the plasma vessel behind the PFC is controlled by water cooling loops on the outside and can be heated up to 150°C.

To satisfy the particular requirements of the various heating methods and to adapt the wall protection to the local geometrical constraints, a combination of these concepts will become necessary in special areas.

Each divertor unit will be equipped with a turbo-molecular pump (TMP) and four cryopumps. The TMPs are the basic pumping system of W7-X. They will provide an effective pumping speed for H_2 of 4200 l/s each. The base vacuum will be < 10^{-8} mbar. Problems with the TMP for long pulse operation are due to the stray magnetic field of W7-X. In a test with a TMP with nominal pumping speed of 5000 l/s, a field in excess of 3-5 mT reduced the frequency of rotation and increased the temperature of the rotor to unacceptable values. This will be investigated further. Possible solutions are to put the pump into a lower field region (this will reduce the pumping speed), to use smaller units (this will increase the cost) or to provide a magnetic shielding. The four cryopumps will have an overall pumping speed of 15.000 l/s for hydrogen. Regeneration will be necessary after appr. 3 hours of operation due to saturation of the pumps.

3. The Heating Systems

3.1 Electron Cyclotron Resonance Heating

A detailed description of the ECRH system is given in [5]. 10 MW of heating power are required to achieve the envisaged plasma parameters. The standard heating scenario is 2nd harmonic extraordinary-mode with 140 GHz at 2.5 T launched perpendicularly to the confining magnetic field from the low field side. This scenario has complete absorption of the irradiated microwaves in a single transit through the plasma at all relevant plasma parameters. This is of high importance for steady state operation from the point of view of protection and cooling of the inner vessel wall.

The steady state aspects concern the gyrotrons, the windows, the elements of the optical transmission line, the inner wall and the conditions along the transmission path.

The total ECRH power is generated by 10 gyrotrons with 1 MW output power in cw-operation each. The gyrotrons will have a depressed collector for electron beam energy recovery, which results in an efficiency of > 45 %. Prototype gyrotrons are presently being developed with industries. For the windows, large diameter (106 mm) edge cooled diamond disks will be used with very low loss-tangent.

Based on the excellent experience at W7-AS

(140 GHz/0.8 MW) an optical transmission line for W7-X was chosen. It is the most simple, reliable and cost effec-tive solution with respect to steady state operation. The advantages are: Very high power capability due to low power density, low diffraction loss of unwanted higher-order free-space modes, low Ohmic losses, no need for special waveguide sections to compensate thermal expansion of the waveguide, and minimum number of parts. The millimetre wave power will be transmitted via two multi-beam waveguides (MBWG) with a length of about 50 m which combine five individual rf-beams each. Central part of the MBWG are the various mirrors. To reach the theoretical predictions of high transmission efficiency, the design of these mirrors [6] must guarantee a stable surface under different heat loads imposed by the millimetre waves. The design finally chosen consists of a 60–70 mm thick honeycomb structure from stainless steel and a thin sheath of copper on the mirror surface. The cooling channels are situated directly below the copper and form one or several spirals. Width, depth and the number of spirals is varied to adapt it to the different mirror shapes and dimensions and to match the local heat transfer to the distribution of the heat load. With this design thermal expansion and deformation is small. The increase of the copper surface temperature with microwave loading (typ. 2 kW per mirror) can be kept below 20 °C and the deviation from the original surface of < 1 μm in steady state is negligible.

The transmission of the power along the 50 m of the MBWG calls for special attention to the humidity or cooling of the air. At standard conditions, 500 kW will be lost due to absorption by the water in the air. This has either to be cooled away by an appropriate air conditioning system or it has to be reduced by reduction of the humidity, which may be difficult to obtain because of the water content of the concrete. A combination of both measures will be used.

3.2 Ion Cyclotron Resonance Heating

At present, ICRH will be used only in the pulsed mode. Two generators with 2 MW each will be available with a pulse length of max. 10 s every 5 min in a frequency range from 30 to 115 MHz. To upgrade the generators and the transmission lines for cw-operation would need development work especially concerning the cooling of ceramics and feedthroughs. The other components of the ICRH system like the antenna loops, the limiters, the faraday screens etc. are more subject to heat load from the plasma and have to be designed for cw-operation from the very beginning.

3.3 Neutral Beam Injection

The neutral beam injection system for W7-X is based on the injection system for the ASDEX-Upgrade tokamak which is described in [7]. It will consist of two beam lines in counter-directed positions, which can be equipped with four ion sources each, delivering up to 20 MW to the plasma. In the first stage only one ion source is used per beam line which can produce 95 A at 55 kV for hydrogen, 80 A at 60 kV for deuterium. In the second stage eight sources with 65 A, 100 kV are envisaged. To stop the beams for conditioning of the injector and to handle the residual ions during the injection phase, panels are used which can handle power densities of more than 25 MW/m^2. Ion sources and panels are actively cooled, i.e. they can run in cw-mode. However, for long pulse operation, sputtering of the ion dump may limit the lifetime.

Other parts of the beam line like the neutraliser and the beam scrapers are designed for 10 s operation only and have to be replaced by actively cooled structures. The main limitation in pulse length is the pumping system which is based on titanium evaporation pumps. These pumps will saturate after 10 s. For longer pulses, they have to be replaced by conventional chevron type cryopumps which fit into the geometry of the titanium pumps (same size and pumping speed). The refrigerator plant for W7-X already includes the additional power load by these pumps.

For both heating systems (ICRH and NBI) the high voltage power supply (5.2) and the cooling system (5.5) have to be upgraded.

4. Control, Diagnostic and Data Acquisition

4.1 The Control System

The main objective of the control system for steady state operation is to ensure a most flexible use of the long pulses for a number of different experiments during one discharge. The configuration of the experiment, including the diagnostic and the data acquisition will be determined within periods of time with variable length (segments) by software programmes, defining the set of experimental and technical parameters for each segment. Special segments will be used for start up, transition between segments and shut down. Initially, the order of the segments will be prescribed before the discharge starts. In a later stage an automatic optimisation is planned, based on the experimental results and the available resources of the experiment.

Every component (heating systems, power supplies, refrigerator etc.) has its own control system for local and independent operation. The coordinated action of the components is guaranteed by the central control computer which triggers the start of the different segments and controls the necessary interlocks to avoid dangerous mutual effects.

The units for operation and display are separated from the real time tasks and are connected via Internet. This increases the safety and flexibility of the system and allows remote operation.

Industrial type parts will be used wherever possible. For ambitious real time tasks which can not be handled with PLCs, PCs will be installed, using the real time operation system VxWorks. Signals within a component will be exchanged by Profibus, between components via dedicated Ethernet connections. All systems will be synchronised by a central clock.

4.2 Diagnostic and Data Acquisition

A detailed description of the diagnostic is given in [8]. A first goal of W7-X is the experimental verification of the major design elements: Selection of iota = 1 with moderate shear, improved equilibrium, particle drift optimisation, energetic particle confinement, negligible bootstrap current and the role of the drift optimisation on anomalous transport. There will be about 50 different plasma diagnostics at different stages. The steady state aspects of the diagnostic mainly concern the thermal stability of the parts exposed to the plasma, the effect of the ECRH microwaves on dielectric material and the large amount of data.

All diagnostics must be able to collect and store acquired and reduced data continuously. An object oriented approach for software design will be used. Since the relation to the actual time is so important in a continuously operating system, all collected data will be marked by a timestamp, which can have a resolution of up to 10 ns. It is planned to have no additional classification of the data corresponding to pulse numbers. The global system time is distributed in a star like network from a central timer system. The data will be archived in an object oriented database.

The continuous operation of the experiment also requires the monitoring of several important signals from the experimental control system as well as from diagnostic subsystems. Every system user will be able to sign on to various monitor signals for observation of the plasma behaviour.

Diagnostic systems with high data rates and a large amount of channels must be designed to reduce data before archiving. Reduction is mainly done on physical basis or by event dependent change on sample rate. When necessary the reduction can be done in parallel by multiple CPU's.

5. The Peripheral Installations

5.1 The Main Supply for the Experiment

The distribution system for the electrical power for the institute and the experiment is very flexible. The power can be drawn from two different sources: The basic supply for the institute is provided by the Greifswald utilities, delivering a power of 5 MVA at a 20 kV level. This power has the standard stability of the utilities and is mainly used for the infrastructure of the institute and some basic installations of the experiment. The electrical power for the heating is drawn from the main 110 kV grid of Mecklenburg–Vorpommern. A power of up to 43 MVA can be used for an unlimited time. This power has a stability of +10/–15 % and is stepped down to the 20 kV level. Provision is made to double this power later for stage II heating. The power supplies for the cooling systems, the refrigerator and the magnets power supply can be connected to both supply nets. This scheme makes it possible to have sufficient power all the time for basic supply and to have the possibility to run the experiment at reduced parameters if one of the supplies fails.

5.2 Power Supplies for the Heating Systems

These power supplies have to energise the three heating systems of W7-X. The parameters of these systems, as seen by the power supplies are listed in Table 2.

The power supply will be modular. Eight modules, rated 65 kV, 50 A (cw) or 130 A (15 s) will be used for ECRH or NBI(I). Always two modules can be put in series to get the necessary voltage of < 130 kV for NBI (II). Two modules, rated 32.5 kV, 100 A (cw) or 130 A (15 s) will be used for ICRH or in the series connection for the remaining two ECRH gyrotrons. The modules will be based on the pulse step modulator principle,

Table 2 Parameters of the high voltage power sup-ply for the heating systems.

Heating System	Voltage	Current	Pulse length	number of users
ECRH	≤ 65 kV	≤ 50 A	cw	10
ICRH	≤ 32.5 kV	≤ 130 A	≤ 15 s	2
NBI (I)	≤ 65 kV	≤ 100 A	≤ 15 s	2
NBI (II)	≤ 130 kV	≤ 130 A	≤ 15 s	8

where regulation and protection is integrated into the 80 single 1 kV modules.

5.3 The Magnet Power Supply

For the supply of the seven groups of coils, seven identical power supply modules will be used. The power supplies have a rating of ± 30 V, 20 kA, which is sufficient voltage to allow a ramp rate of 30 A/s. During operation a voltage of appr. 3 V is expected due to the Ohmic losses in the busbars and the feedthroughs. The total losses will be in the order of 500 kW. Since the magnet will be operated continuously during the daytime this power represents a non negligible load for the cooling of the experiment.

For the protection of the coil system during a quench seven nearly identical fast discharge system will be used which can dump the stored magnetic energy into dump resistors with a time constant < 5 s. After a quench some hours are necessary to cool down these resistors and to restore the functionality of the system.

5.4 The Refrigerator

The cooling power will be supplied by a refrigerator. A total of 2500–3500 W at 3.3–4.2 K and 50.000 W at 60–80 K will be necessary, the actual needs depend on the design of the current leads. Conventional copper current leads may require a power up to 2 kW, for HTSC type current leads only half of this value may be necessary.

5.5 The Water-Cooling System

Depending on the efficiency of the gyrotrons a cw-power of up to 28 MW has to be cooled away. Either a large cooling tower or a large amount of ground-water would be necessary. For economic and environmental reasons it was decided to restrict the maximum pulse length to < 30 min. Therefore it is possible to subdivide the cooling into an inertial part, where the actual power heats up a reservoir of 1200 m^3 of water by ≤ 15°C and an active part, where cooling towers with a capacity of 5.5 MW cool down the water in a second 1200 m^3 reservoir to ambient temperature. The experiment can start in the morning with a 30 min ECRH pulse together with 10s NBI/ICRH pulses every 5 min. After three hours of cool down, pulsed operation (10s / 5 min) is possible. At the end of the day another 30 min pulse can be made.

The cooling system for the ECRH and the PFC will be designed to allow cw-operation from the very beginning, the cooling for NBI and ICRH will have active characteristics for 10 s and inertial cool down for the 5 min inter-rupt time.

5.6 Radiological Aspects

A detailed study is given in [9]. Two limits have to be considered: The restriction of the radiation outside of the building and of the activation of the structure of the experiment. W7-X is not designed for D-T operation, therefore only the D-D reaction is the source of radiation. With the envisaged plasma parameters only a NBI heated plasma can generate a considerable amount of neutrons. The total time for NBI DD-plasma operation at high power will be restricted to 500 pulses with 10 s per year, giving an averaged neutron rate of 10^{12} s^{-1}. With this value, access to the machine is always possible within a few days and no remote handling tools are necessary, To reduce the long-term activation, special attention is paid to the Cobalt content of the steel. 500 ppm are allowed in the various parts of W7-X proper. With this value hands on disassembly of W7-X without any radiological precautions is possible 10–15 years after shut down.

6. Conclusions

WENDELSTEIN 7-X will be the next element in the stellarator line of the IPP on the way to a fusion power reactor. Besides the many physics aspects of optimisation of the stellarator special attention has to be paid to the inherent capability of steady state operation. All elements of W7-X proper are designed to fulfil this requirement. Although some components of the periphery are limited at present to short (10 s) or long (30 min) pulse operation, they could be upgraded to continuous operation at a later stage if necessary.

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