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Technical Challenges of the WENDELSTEIN 7-X Stellarator

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Abstract

WENDELSTEIN 7-X (W7-X) is an optimized advanced stellarator and continues the successful stellarator line of the IPP Garching. W7-X will be built at Greifswald and will exploit the inherent capability of the stellarator principle for stationary operation and aims to demonstrate its basic qualification as a power plant. The technical challenges of the major components of W7-X are being described in detail.

Keywords:

fusion reactor, W7-X, stellarator, superconductivity, ECRH

1. Introduction

In the frame of the European programme of concept improvements of fusion devices IPP is pursuing the optimized advanced stellarator line with W7-X being presently under construction at the Greifswald branch of the IPP.

W7-X is based on a HELIAS configuration (HELIcal Advanced Stellarator), which is optimized to achieve the following criteria for reactor grade plasmas [1]:

- high quality of vacuum field magnetic surfaces,
- low Shafranov shift to allow operation at high β-values,
- good MHD stability properties,
- small neoclassical transport in the long-mean-free-path regime,
- small bootstrap currents so that the design properties of the magnetic configuration are not lost at high, β
- good collisionless α-particle confinement at finite β-values

The purpose of W7-X is to demonstrate the fusion reactor relevance of the HELIAS in a relevant plasma regime. The foreseen plasma parameters are peak temperatures in the 5 – 10 keV range, densities up to 3×10^{20} m^{-3}, averaged β-values up to 5 % and a triple product ($n\tau T$) up to 3×10^{20} keVsm^{-3}. To achieve these conditions a heating with 10 MW of ECRH, 4 MW of ICRH and 4.5 – 18 MW of NBI is foreseen.

In addition to the physics aims of this experiment, a number of technical objectives will be tackled:

- The inherent stellarator property of continuous operation will be demonstrated up to a pulse length of 1800 s. This calls for a superconducting magnet system, a continuous heating method based on ECR, an appropriate handling of the power and particle fluxes by the divertor system as well as sophisticated diagnostics.
- To demonstrate a reactor relevant design, W7-X will be modular. The device is not built for Tritium operation.
- The W7-X proper will offer considerable flexibility in operation. To change the magnetic field configuration, supplementary coils will be installed. For diagnostics numerous ports will allow the access to the plasma column.

The development and verification of critical W7-X items started well ahead of the project. This holds for

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Corresponding author's e-mail: wan@ipp.mpg.de the superconducting cable, the non-planar coils, the cryostat and the divertor target elements.

2. Magnet System

The optimized plasma confinement asks for dedicated magnetic flux surfaces, which in turn determine the external current distribution. These surface currents are further structured to define finally the winding geometry of the 50 nonplanar main field coils. Taking into account the fivefold axial symmetry of W7-X and an additional dihedral symmetry within each module the number of different coils is reduced to five. Each coil is wound by 120 turns resulting in a total nominal current per coil of 1.92 MA and a maximum field of 6.2 T at the coils resp. 3 T on the plasma axis. A sketch of the coil system is given in Fig. 1.

NbTi cooled to about 3.8 K was selected as conductor material. A cable in conduit conductor (CICC) was developed. Based on standard strands with a diameter of 0.59 mm and 144 filaments 243 strands are cabled. A void fraction of approx. 37 % ensures sufficient internal cooling by liquid helium at moderate pressure drop. The mechanical strength of the cable is provided by an AlMgSi1 jacket applied by a conventional co-extrusion process. This alloy features sufficient flexibility during the winding process and can be hardened at 170 °C prior to impregnation of the winding package. Trials on some kilometres of cable give confidence in an efficient production of the full length of 60 km for W7-X. The required nominal current of 16 kA/per cable was experimentally verified with a safety factor of 2.

The nonplanar coils are wound into high precision moulds. In contrast to circular coils the conductor is not under tangential stress during winding. Similar to the production of the W7-AS coils, the conductor has to be in a "soft state" to be pressed into the curvatures and to be fixed by clamps (see Fig. 2). The winding package will be glass tape insulated prior to a vacuum resin impregnation. After quality tests it will be encapsulated in the two halves of a cast steel casing, which will be closed by circumferential welding seams. Embedding will be done with reinforced resin.

The supplementary set of 20 planar coils will be manufactured following usual methods using the same cable.

A full size nonplanar DEMO-coil with a diameter of about 3.5 m is now approaching completion. The conductor concept proved to be successful and the dimensions of the winding package could be realized with tolerances of 3 mm only. The assembly of the coil casing made from segments by welding resulted in unexpected low tolerances of only some millimetres. The work for the procurement for the final 50 coils has

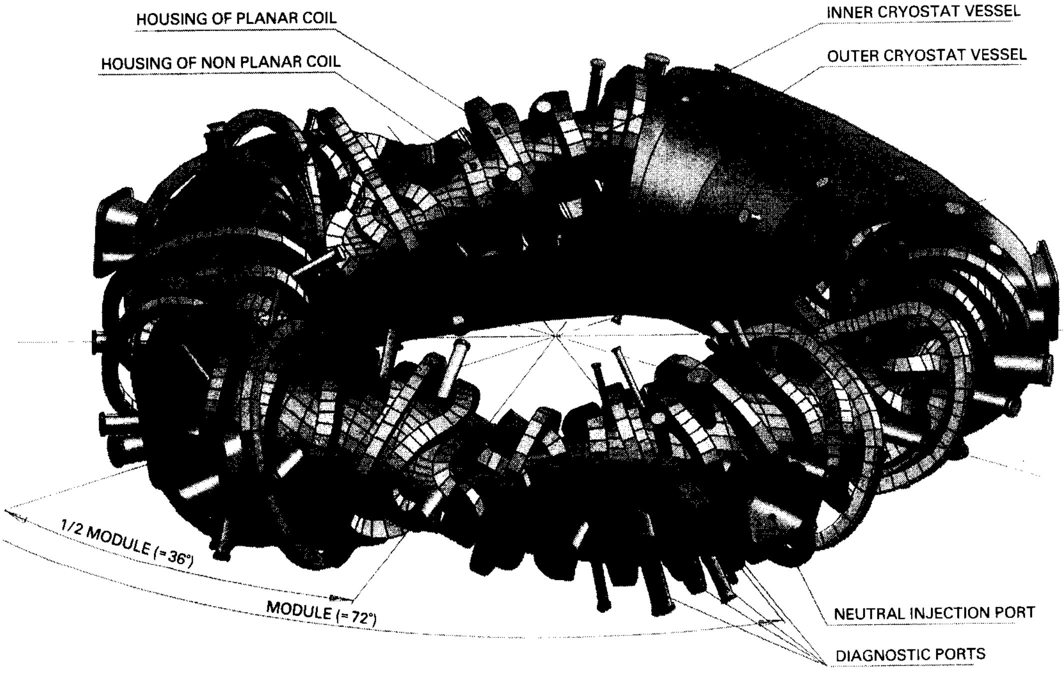

Fig. 1 Configuration of the W7-X coil system.

started.

The magnetic forces in the coils are transmitted by the embedding to the steel casing. Residual forces are balanced by a toroidal vault structure between the coils. The centripetal forces in the coil system are taken by toroidal stiffening rings. Carefully designed low conductivity support legs carry the 350 t cold structure at cryogenic temperature.

3. Cryostat

The W7-X cryostat has to provide a vacuum insulation for the superconducting coils and the cold structure. Its main parts are the plasma vessel, which also serves as the inner wall of the cryostat, the outer vessel and the ports connecting both vessels. Thermal protection is provided by vacuum superinsulation and a radiation shield at 60 – 80 K.

In order to minimize the magnet dimensions the plasma vessel has to follow closely the plasma envelope. This means that within each of the five modules the cross section of the vessel changes from bean-shaped to triangular and back again. The vessel must have enough space for the in-vessel components while keeping them at a safe distance to the plasma and provide clearance for the thermal insulation of the coils and allowance for coil assembly. These conflicting requirements demand tight construction tolerances of only 20 mm as compared to the major diameter of 11 m. Therefore design and construction of the plasma vessel were pushed to their technical limits. This is presently demonstrated in a DEMO-cryostat, which comprises a full scale 1/8-torus using dummy coils. The manufacture of the plasma vessel was realised by welding bended steel sheet stripes in poloidal direction (see Fig. 3) – a similar technique as for the vessel of W7-AS. Further constraints result from the need to bake-out the plasma vessel to 150°C and to cool-down the coil system to cryogenic temperatures. The first leads to 15 mm thermal expansion of the plasma vessel radius, which has to be compensated for by bellows at the ports. The latter further reduces the clearance between the coils and the plasma vessel.

Several forces act on the plasma vessel: weight, atmospheric pressure, unbalanced vacuum and spring forces from the flexible ports and eddy current forces during coil emergency discharges. Although stellarator plasmas are stable, eddy currents caused by externally forced plasma quenches will be considered as well as electromagnetic forces acting on the heat radiation shields.

The cryostat is penetrated by approx. 300 ports, which are used for diagnostics, control, supply, heating, evacuation, operation, maintenance, etc. Although most of them have a circular cross section, about 40 are oval or rectangular with free cross sections of up to $0.4 \times 1\ \mathrm{m}^2$. These ports have to pass the coil housings, the electrical terminals and the support structure. Again thermal movements, insulation, and mounting tolerances have to be taken into account.

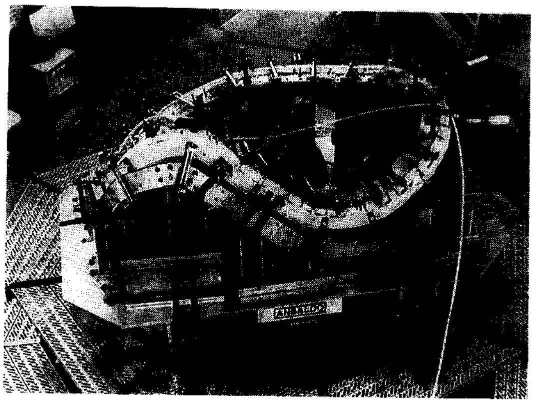

Fig. 2 Demo coil during winding (by courtesy of Ansaldo).

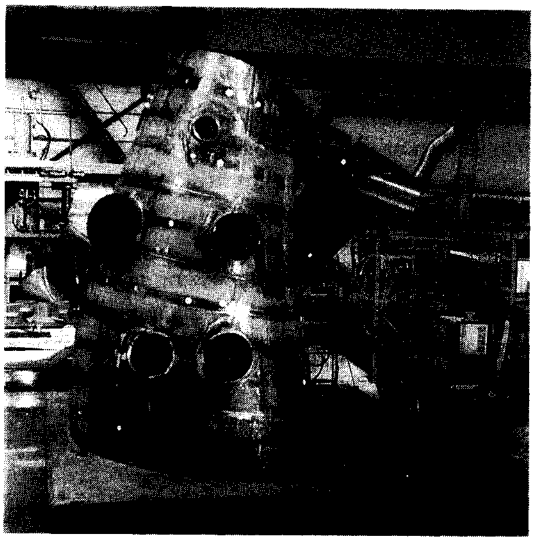

Fig. 3 Assembly of the plasma vessel (by courtesy of Balcke Dürr).

The mounting procedure for the cryostat is presently being tested during the DEMO-cryostat construction. First the coils and the vault structure are preassembled and adjusted onto the support structure. Due to the small clearances the coils have to be dismantled again and "threaded" onto two separated but already thermally insulated halves of the plasma vessel sector.

Final fixation and adjustment of the coils to their supports can be performed only parallel to the final welding of the plasma vessel. After integrating the vault structure elements between the coils this whole assembly is put into the lower half of the outer vessel. The ports are mounted after closing the outer vessel with its upper half. Such modules will later be transported to site for final assembly of W7-X.

The cryostat interacts closely with the in-vessel components, which are required for power absorption and particle exhaust. The plasma facing wall is armoured by water cooled graphite or B_4C tiles. The peak heat loads of up to 10 MW/m^2 are controlled by actively cooled target elements.

The cryogenic cooling requirements are very specific for the individual components. The conductors of the nonplanar and planar coils as well as the coil housings and support structure require supercritical helium at $\leq$ 3.8 K and $\leq$ 4.2 K, respectively. The current leads and the heat radiation shields are cooled by He gas. Adding all cryogenic consumption results in an equivalent refrigeration power of approx. 4.5 kW at 4.0 K. Optionally high temperature superconductor current leads are being studied, which would reduce the cryogenic load by up to 30 %. The cooling requirements crucially vary with the W7-X operation modes. Hence an economic but flexible refrigeration system is needed, which in addition has to supply refrigeration for cryovacuum pumps and LHe for laboratory purposes.

4. Electron Cyclotron Resonance Heating System

ECR-heating is foreseen as the basic heating system for steady state operation at reactor relevant plasma parameters with a total microwave power of 10 MW.

The microwave power is generated by 10 gyrotrons operating at 140 GHz, each providing 1 MW continuously. The loss power handling puts severe demands on the design and the cooling of the gyrotrons tubes and of the output windows. For economic reasons the efficiency should reach 50 %, which can be achieved by energy recovery within the tubes.

The transmission of the microwaves is achieved by optical means only. Near to the gyrotrons cooled matching and polarizing mirrors are installed for conditioning the gyrotron beams. At the stellarator the beams are guided to six ports, which are equipped with steerable launchers.

One original sized highly efficient transmission line is currently under construction at IPF Stuttgart. It aims to verify the analytical results and to derive the thermomechanical properties of optical components featuring a large bandwidth, low mode conversion and good imaging quality.

Reference

[1] G. Grieger *et al.*, Phys. Fluids B **4**, 2081 (1992).