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Steady-State In Vessel Components for the WENDELSTEIN 7-X Stellarator

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The WENDELSTEIN 7-X (W7-X) stellarator, presently under construction in Greifswald, Germany, will be a “fully-optimized” stellarator device with the aim to demonstrate the reactor potential of the HELIAS line at steady operation close to fusion relevant parameters.
The in-vessel components of W7-X are designed for steady state operation with high heat flux divertor target plates designed to withstand 10 MW/m^2 power loading. The plasma vessel and the ports are further protected by a series of water cooled graphite tiles clamped on CuCrZr cooling structure and of stainless steel panels. Behind the divertor components are the cryo vacuum pumps and the sweep/control coils.
For the first operation phase in 2014, an inertial cooled divertor of the same geometry as the high heat flux divertor will be installed as well as all in-vessel components except cryo vacuum pumps. Mostly, the components will be operated without water-cooling since during this phase the power will be restricted to 8 MW for 10s and 1 MW for 50s.
This paper describes the selected technical solutions and the present status of the various in-vessel components of W7-X with a focus on the high heat flux divertor.

Keywords: WENDELSTEIN 7-X, stellarator, in-vessel components, divertor, wall protection.

1. Introduction

The experiment WENDELSTEIN 7-X (W7-X), at present under construction at the Greifswald branch of the Max-Planck-Institut für Plasmaphysik (IPP), with a superconducting magnet system and actively cooled in-vessel components (IVC), is the largest stellarator project to date [1]. The design of W7-X will allow steady state operation, with a 140 GHz ECRH cw input power of 10 MW over a pulse length of up to 30 min. Additional heating sources, ICRH and NBI, will provide additional power for flexible experimentation [2]. The IVC, shown in Fig. 1, consist of the divertor and the wall protection of the plasma vessel. Behind the divertor components are the cryo vacuum pumps (CVP) and the sweep/control coils (CC).

For the first operation phase in 2014 [3] an inertial cooled divertor (TDU) will be installed, this will be replaced later for steady-state operation by the high heat flux (HHF) divertor. The TDU has the same geometry as the HHF divertor. This phase aims at determining the correct positioning of the target plates. This approach will minimize the necessary commissioning of the HHF divertor in steady-state operation.

The other IVC except CVP will be installed at the beginning but mostly operated without active water cooling. This is possible as the input power will be restricted to 8 MW for 10s and 1 MW for 50s. This paper presents the selected technical solutions and the present status of the IVC.

The complete IVC have a weight of 33.8 tons, covering a total surface of 265 m^2. The intrinsic challenge of this project is the 3D-geometry of the machine and the limited available space within the vacuum vessel. IVC

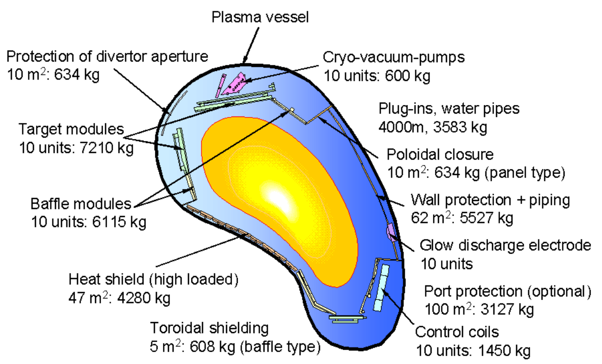

Fig.1 Location of IVC in the W7-X plasma vessel at the “bean-shape” cross-section.

author’s e-mail: *Reinhold.Stadler@ipp.mpg.de* have been designed to maximize the plasma volume and require a high level of accuracy.

2. IVC Project

The development and construction of the IVC is managed in IPP Garching, in close cooperation with the team at IPP Greifswald.

A large part of the IVC is manufactured and tested in the IPP Garching workshop. The manufacturing contract for target elements (TE) of the HHF divertor has been awarded to PLANSEE SE, Austria. The sweep/control coils have been manufactured by BNG, and the wall panels (WP) are being delivered by MAN-DWE, both companies are located in Germany.

3. Divertor Components

The divertor consists of ten similar discrete units, arranged above and below in each of the five modules. The plasma facing components are the target modules (TM) and the baffle modules (BM). Behind them are the CVP and CC. The highest thermally loaded parts are the target plates with a surface area of ~25m² to allow a wide range of plasma configuration and magnetic parameters.

3.1 High Heat Flux Divertor

The ten similar units of the HHF divertor are divided into nine horizontal and three vertical TM, with an intermediate pumping gap between horizontal and vertical TM. The horizontal part consists of four HHF-TM, two clamped low heat flux modules (LHF) and three additional HHF-TM in a row along the toroidal circumference.

Each HHF TM consists of eight to twelve actively cooled TE (Fig. 2). The HHF divertor requires the production of about 900 TE of 13 different types. These

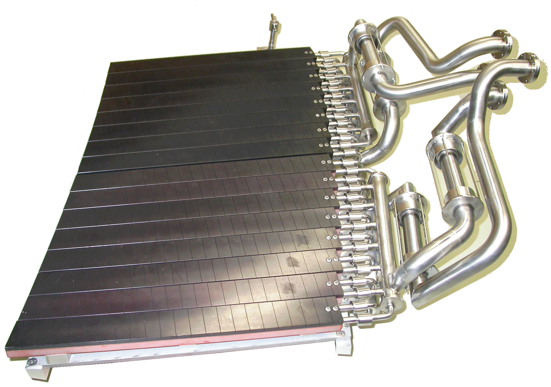

Fig.2 Two full scale prototype HHF target modules with dummy target elements, already mounted on adjustable frame.

Fig.3 GLADIS HHF-test facility, with new designed vacuum lock

elements are each designed to remove a maximum power of 100 kW and to withstand a steady-state heat load of 10 MW/m².

The design comprises flat carbon fiber composite (CFC) tiles bonded to actively water-cooled CuCrZr heat sinks. For the TE production, the initial approach was to use as much as possible well-known technologies. A large experience in the manufacturing in large quantities of HHF elements designed for similar loading conditions was gained during the fabrication of about 600 finger elements for the toroidal pump limiter of Tore Supra [4]. The contract was awarded to the same company that successfully produced these finger elements, in order to avoid significant R&D activities. The strategy consisted of a preliminary phase of pre-series activities to qualify the manufacturing process to be adapted to the different geometry of target elements (longer, wider, trapezoidal), followed by the launching of the serial fabrication of the required 900 elements.

In addition, Sepcarb® NB31 CFC material was selected instead of N11 for Tore Supra produced by the same company, namely Snecma Propulsion Solide, France. This grade offers higher mechanical properties to cope with the loading occurring during the fabrication and operation at the critical interface between the CFC and Cu. Many unexpected difficulties occurred during this fabrication and significant differences in the obtained mechanical properties between delivered batches were observed. This required substantial additional qualification activities, and approximately 900 kg CFC was finally successfully delivered to IPP.

The heat sink is manufactured by joining by electron beam welding two plates of CuCrZr into which have been machined semi-circular channels. Swirl tapes are inserted and the plates are welded together. This design can suffer from leakage between adjacent channels with a

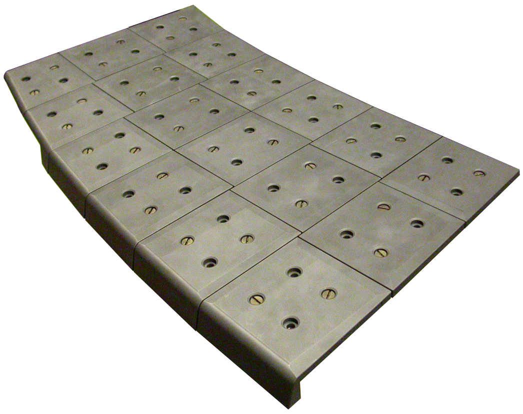

Fig.4 Baffle Module with graphite tiles temporarily clamped during acceptance tests.

significant reduction of the thermal performance which affects the critical interface with CFC tiles. Additional efforts have been dedicated to the improvement of this weld design.

The bonding technology between CFC tiles and heat sink underwent also significant improvement. The initial Active Metal Casting (AMC) technology will be improved by a bi-layer technology: a copper layer is active metal cast to CFC tiles, and then an OF-copper layer is added by hot isostatic pressing. The tiles are finally bonded by electron beam welding onto the cooling structure, with the same process used by Tore Supra. This solution, as shown in samples, is expected to improve the reliability and the robustness of the bond for all types of TE under thermal cycling, and to avoid or reduce crack propagation at the interface. However, adaptation of the Tore Supra solution to the new geometry showed that several problems have to be overcome resulting in a significant pre-series effort.

About sixty prototype TE have been evaluated during pre-series activities. All elements were tested in the HHF ion beam facility GLADIS (Fig. 3) of IPP Garching in fatigue tests of 100 cycles @ 10 MW/m² for 10 seconds.

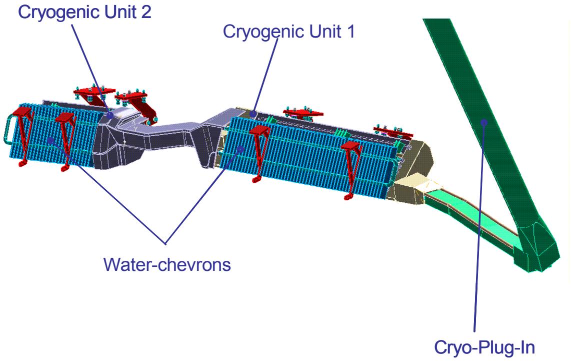

Fig.5 CAD model of Cryo Vacuum Pump

The last delivered elements showed no visible defects at the end of the test campaign. In addition, one element survived 10.000 cycles without visible damage. Tests with increased power were also performed. A critical heat flux of 31 MW/m² was achieved on an element without tiles, compared to the 25 MW/m² specified. A screening test with heat fluxes up to 24 MW/m² was also achieved. With these promising results a sufficient margin for experimental steady-state operation can be expected and shall be verified by an additional development program.

The LHF-units are designed for 1 MW/m² steady-state and use the same technology as the BM. The divertor pumped volume is closed by toroidal and poloidal closure plates. For the toroidal part a water cooled structure similar to the BM is used and for the poloidal closure stainless steel panels are used.

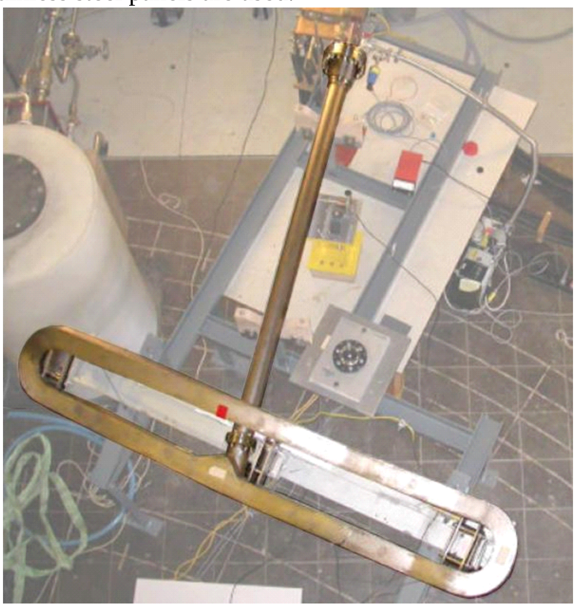

Fig.6 Control coil in IPP test facility.

3.2 Baffle Modules

The 170 BM are designed for a maximum steady-state heat load of 500 kW/m². The BM consists of CuCrZr plates vacuum brazed to stainless steel tubes that form the cooling circuit. Graphite tiles are clamped to the structure using TZM screws (Fig. 4). A compliant layer of soft carbon is used to provide the thermal contact.

3.4 Cryo-Vacuum Pump

The CVP are located behind the horizontal TM in the divertor volume. Each CVP is built up of two units, which are shielded by water cooled chevrons against radiation loads (Fig. 5). The CVP are designed for an optimum pumping speed of 75 m³/s in front of the chevrons.

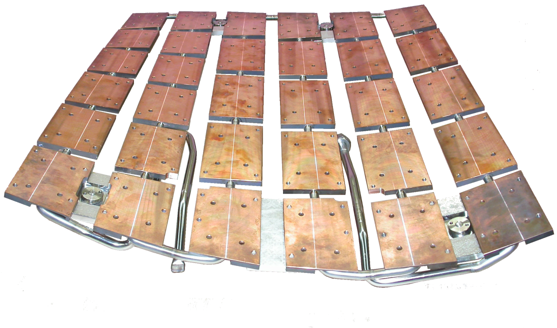

Fig.7 Heat shield, shown without clamped graphite tiles.

3.5 Control Coils

The ten CC (Fig. 6) are located behind the BM. The CC allow to compensate for symmetry breaking error fields and to sweep the strike point and spread the power deposition along the target surface in order to increase steady-state reliability of the TE.

4. Wall Protection

The plasma vessel wall and the ports are protected by actively cooled components. On the inboard side, close to the plasma surface, graphite protected heat shields (HS) are installed. The outboard side is covered by stainless steel wall panels (WP).

4.1 Heat Shields

The HS (Fig. 7) use similar technology to the BM, but are designed for a maximum heat load of 300 kW/m^2. Some of the 162 HS include beam dump elements for the neutral beam injection (NBI), the ECRH heating and the diagnostic-injector, as well as special solutions for integrated diagnostics systems.

Fig.8 Wall panel, rear view.

4.2 Wall Panels

The outboard region of the plasma vessel and the pumping gap area will be covered by 320 steel WP (Fig. 8). They are designed for a heat load of up to 200 kW/m^2.

For the layout of the WP, the plasma vessel geometry was divided into facets with small cylindrical shaped segments. This reduced significantly manufacturing effort by allowing 1D-bending on the individual WP.

Each WP is made from two stainless steel sheets that are welded together and quilted by overpressure to form a meander of cooling channels. Along the circumference a vacuum tight weld seals the WP.

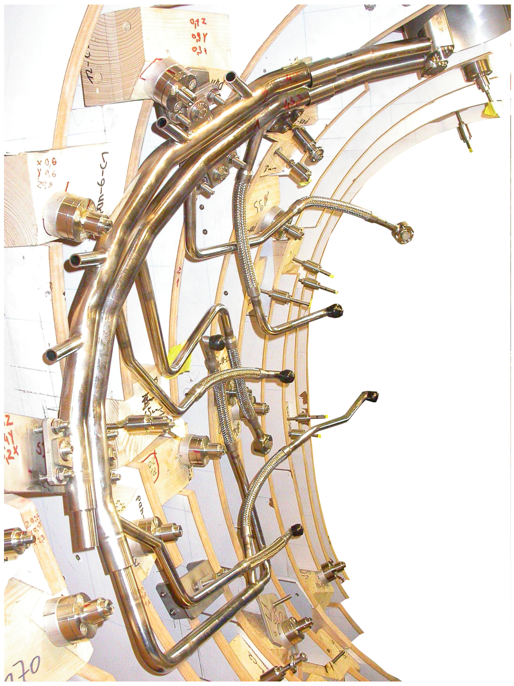

Fig.9 Prototype cooling circuit during installation in the wooden mock-up.

4.4 Port Liner

Some ports, that require internal protection during HHF operation, are equipped with WP-type port liners. The NBI ports – due to the higher thermal loads - will be equipped with graphite and CFC tile protection similar to the BM.

5. Internal Cooling Supply

All 1500 plasma facing components are actively cooled during steady state operation. 4.5 km of pipe work is installed as 150 individual cooling loops. The cooling circuits are the first to be installed. Design and manufacturing technology were verified with a prototype, installed and hydraulically tested in a wooden mock-up of a plasma-vessel segment (Fig. 9).

7. Test Facilities used for the IVC-activities

Several test facilities are used regularly to perform acceptance tests of all IVC.

A vacuum chamber, with 3 m length and 1.2 m diameter, is used for leak and out-gassing tests (Fig. 10), hot leak tests for the plasma facing components at (160°C) and cold tests at LN2 temperature for the CVP.

Hydraulic tests and temperature distribution analysis to identify hot spots on the WP with an infrared camera are also used.

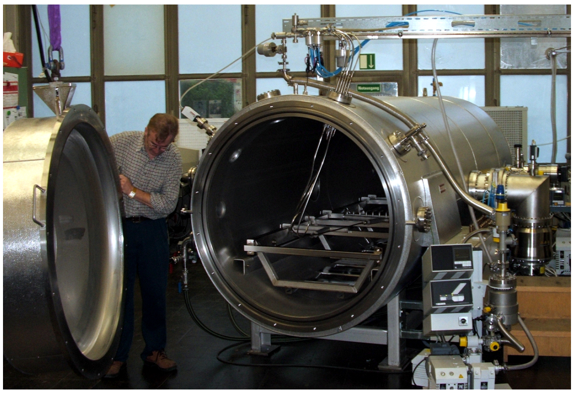

Fig.10 Vacuum chamber for testing of IVC-components.

8. Conclusions

The IVC for W7-X are designed for steady-state operation at 10 MW and the components are actively cooled.

Prototype HHF testing has shown encouraging results for the development of the technology for the standard TE. A significant development program is still required before all 13 types of TE for W7-X are fully qualified. Manufacturing of the HS, WP and BM is well progressed. Procurement of graphite tiles is on-going. Serial production of the cooling loops was initiated, all CC are delivered. First delivery of the components to IPP Greifswald has started.

The present time schedule, based on the experience gained throughout the project, shows that all components, including the TDU, will be available for installation to allow machine commissioning in 2014.

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