OPERATION AND ENGINEERING OF THE POWER AND PARTICLE EXHAUST IN WENDELSTEIN 7-X

H. Grote, J. Boscary, H. Greuner[1], J. Kisslinger[1], B. Mendelevitch[1], H. Renner, D. Sharma

Max-Planck-Institut für Plasmaphysik, Euratom Association
Teilinstitut Greifswald, Wendelsteinstr. 1, D-17491 Greifswald, Germany
[1]Max-Planck-Institut für Plasmaphysik, Euratom Association
D-85745 Garching, Boltzmannstr. 2, Germany

Abstract

The divertor and the pumping system of W7-X are designed for stationary operation at the full range of magnetic and plasma parameters $(5/6 < \iota < 5/4; \beta < 5\%)$. The target plates, designed to withstand a stationary heat flux up to 10-12 MW/m², are shielded with CFC joined to a CuCrZr heat sink cooled by a pressurised water-flow. The final geometry was optimised to reduce the total target area without narrowing the operational range of parameters. Baffles guide the neutrals to the pumping gap into the divertor chamber and keep the neutral pressure in the main chamber low. The baffle plates are designed to withstand a maximum heat flux of 0.5 MW/m² and consist of graphite tiles clamped on a water-cooled CuCrZr structure.

External particle fluxes injected by NBI, localised gas puffing and pellet injection in a range up to 10^{22} s^{-1} will be applied for heating and controlling the density profiles. These fluxes have to be pumped out to achieve a stationary regime.

The main pumping system of W7-X will consist of turbomolecular pumps (TMPs), connected to the 10 divertor chambers, with their corresponding backing pumps. Cryo-panels will be integrated inside the divertor units. The high pumping speed can be maintained up to two hours.

Introduction

The <u>HELI</u>cal <u>A</u>dvanced <u>S</u>tellarator (HELIAS) WENDELSTEIN 7-X (W7-X) was designed at IPP Garching and is presently build in the institute's branch at Greifswald, Germany.

The experiment aims to demonstrate the reactor potential of this stellarator line at steady-state operation close to fusion relevant parameters. This requires the use of superconducting coils and the installation of a divertor to handle the power and the particle fluxes.

The magnetic configuration of the device has five field periods and was optimised with respect to plasma equilibrium, stability and reduced neo-classical transport in a wide range of parameters [1 – 3]. The chosen magnetic configuration is characterised by inherent divertor properties without the installation of additional coils [4]. The interaction of the divertor target plates with the islands at the boundary or the ergodisation produces a region with open field lines and allows to localise the divertor target plates sufficiently far from the confinement region to screen neutrals and impurities [5]. The target plates have to follow a complex 3-D geometry as the islands are winding helical around the confinement region.

In this paper we discuss the engineering of the divertor structures - responsible for the power handling, and the pumping systems for an effective particle exhaust.

Divertor engineering and operation

For W7-X an open divertor configuration was chosen as a first approach to match the whole operational range of the rotational transform and beta values. Two divertor chambers

are arranged in a mirror-symmetry above and below the helical axis in each of the five field periods. In total, ten divertor units are located along the helical edge of the plasma column. These units consist of the target plates for the dissipation of energy, the baffle plates to guide the neutral particles to the pumping slit and are closed by poloidal and toroidal end plates [6].

The actively cooled wall protection shields the wall of the plasma vessel and minimises the heat transfer to the plasma vessel. These plasma facing components are coated with low-Z material (vacuum plasma sprayed boron carbide on stainless steel) or consist of graphite on a CuCrZr heat sink. They are able to withstand long pulse discharges [7,8].

The main heating system is ECRH with a max. power of 10 MW for max. 30 min duration. The experimental flexibility of the device is increased with additional heating systems such as ICRH with a max. power of 4 MW for max. 30 min duration, and NBI with a max. power of 5 MW for several 10 s intervals per 30 min discharge.
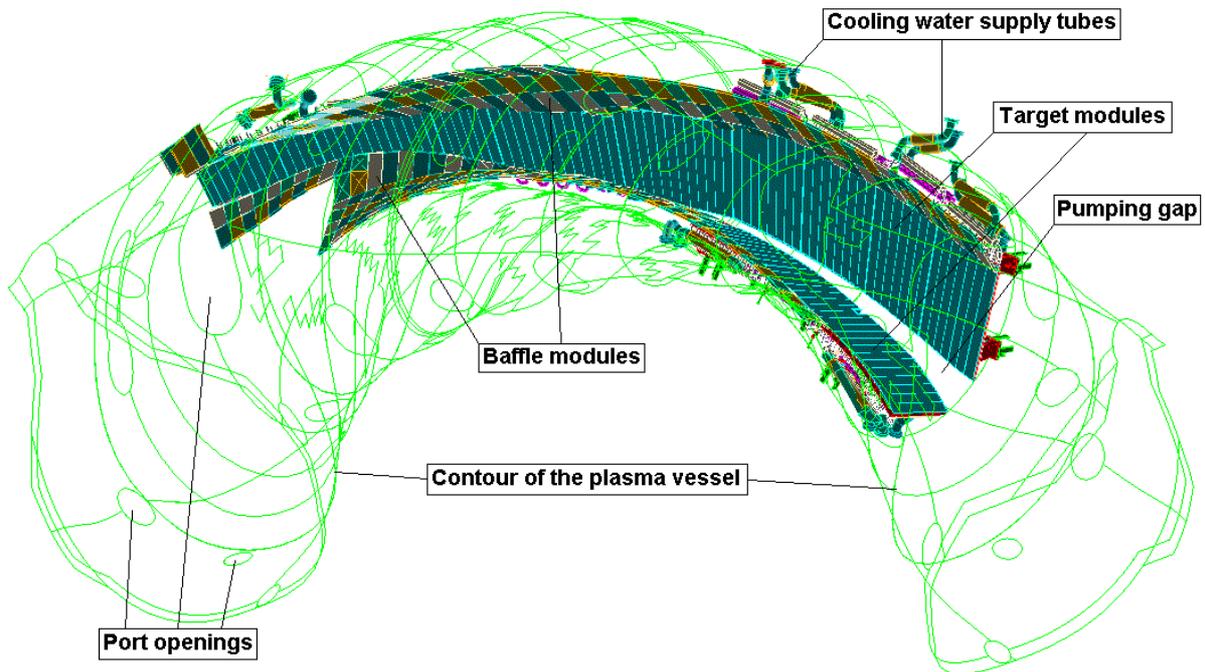

Fig. 1   Overall view of a divertor chamber including the target and baffle modules in the plasma vessel

The divertor concept and design was introduced in detail in [9]. The 3D-shaped surface of the target plates is approximated by a series of plane target elements (Figure 1).

The decision to increase the angle of incidence of incoming particles onto the target plates by 1° allowed to reduce the area of the highest loaded targets from about 30 m^2 to about 20 m^2. The new design of the target plates combines two different technological solutions. The highest loaded areas are designed to withstand stationary heat fluxes up to 10-12 MW/m^2. The selected design is a flat tile made of CFC Sepcarb® NB31 as plasma facing material bonded by AMC® and electron beam welding onto a heat sink made of CuCrZr-alloy - water-cooled by an inner channel equipped with a twisted tape. There are five different basic types of target elements, of a length ranging from 250 to 595 mm and of a width from 50 to 57 mm. For some types, the inboard part facing the pumping slits in the opening of the divertor is also shielded with CFC tiles. Special additional types of target elements dedicated to diagnostics have been designed. Slits of about 10 mm width in the toroidal direction allow experimental studies through the target plates to be carried out. The remaining area is designed to withstand a stationary heat flux up to about 1 MW/m^2 (Figure 2). The technological solution consists of

graphite tiles clamped on CuCrZr heat sinks which are brazed onto water-cooled stainless steel tubes [10].

The baffle plates are designed to withstand stationary heat fluxes up to 0.5 MW/m^2. These plates also protect the water-cooling system of the target elements. The total area of the baffle plates is about 30 m^2. The basic technology is the same as for the lowest loaded areas of the target plates - graphite tiles clamped on CuCrZr heat sink brazed to water-cooled stainless steel tubes.
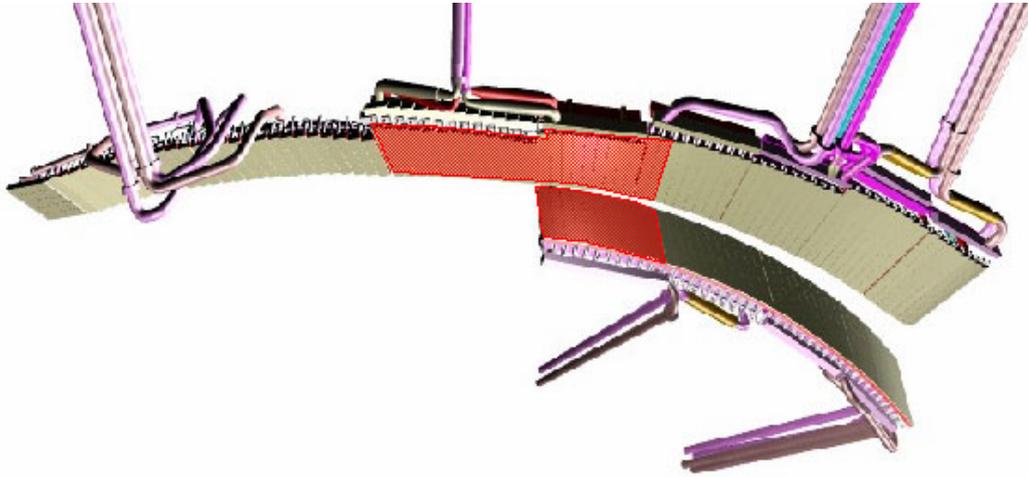

Fig. 2   *Combination of two different technological solutions for the target plates matched to the increased angle of incidence of the incoming particles by 1°. The highest loaded areas withstand up to about 10-12 MW/m^2 (gray). The remaining area for up to about 1 MW/m^2 is marked in orange.*

The wall protection area is about 120 m^2. This plasma facing component is designed to withstand stationary heat fluxes ranging from 200 to 500 kW/m^2 depending on the location. Two different technologies have been selected. For higher loaded areas, it is the same technology as for the baffle plates. For lower loaded areas, cylindrical-shaped water-cooled panels made of stainless steel and covered with boron carbide are used. The thickness of the boron carbide layer is 300 μm.

This modification of the target areas also required the geometrical adaptation of other in-vessel components to this new configuration, like the baffle plates, the toroidal closing plates, the wall protections, the diagnostics, the control coils, and the cryopumps.
With this new configuration, it will still be possible to operate in the full plasma and magnetic parameter space, but further detailed studies are necessary to clear up the action of the control coils and the pumping. First results of the EMC3-EIRENE code [11, 12] with the sampling grid upgraded to incorporate arbitrary magnetic structures confirm the assumptions made earlier concerning the width of the pumping gap [13, 14]. The behaviour of self-consistently generated recycling neutrals was studied in the plasma of the scrape-off layer of W7-X for the standard case ($\beta = 4\%$, ι = 5/5). The average neutral density in the divertor chamber was calculated for a range of divertor openings in order to validate the proposed divertor geometry. Achievable pumping speeds were estimated for a range of pumping efficiencies of the proposed pumping system. An optimum pumping speed of $3.5*10^{21}$ s^{-1} was estimated for a neutral particle density of $1.0*10^{12}$ cm^{-3} in the divertor chamber (Figure 3).

Fig. 3   Dependence of Hydrogen pumping speed
on the width of the pumping gap
(normalised to the actual chosen value A_0).
The parameter α is the pumping efficiency,
here varied from 2 to 10 %. The neutral
density was taken to be $1.0*10^{12}$ cm^{-3} .
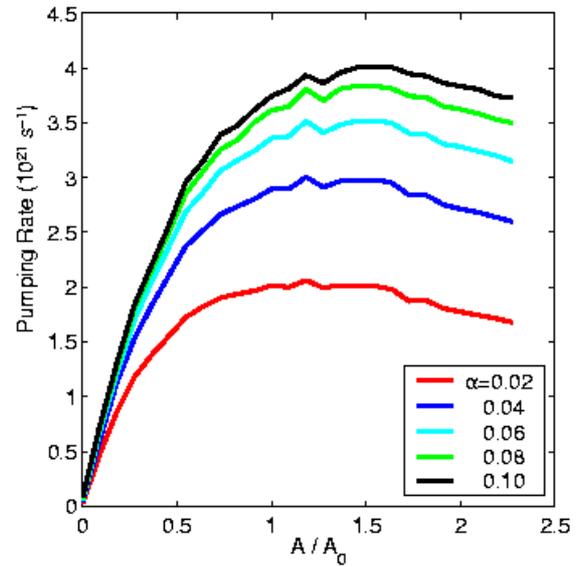
Particle exhaust

The vacuum pumping installation will consist of two independent systems - turbomolecular pumps (TMPs) and cryo-panels.

Each of the 10 divertor chambers will be equipped with two ports (diameter 400 mm) for pumping. TMPs with their corresponding backing pumps will define the basic system for pumping the plasma vessel of W7-X. They will be used for pump down from atmospheric pressure to the base level of 10^{-8} mbar, during conditioning of the vessel as well as during the plasma experiments. Whereas the ten backing pump blocks (two-stage systems consisting of 1,000 m³/h roots-pumps and 65 m³/h rotary pumps to handle high gas loads stationary - will be located far enough from the experiment, the TMPs have to work in the magnetic stray field of the superconducting coil system of W7-X. Consequently the positioning of the TMPs will be a compromise with respect to the effective pumping speed in the divertor chamber and the value of the magnetic stray field. Testing the TMPs of various manufacturers in a variable magnetic field was therefore essential to design the pump lines and fix the positions of the TMPs relative to the cryostat. Including a safety margin, a magnetic field of 7 mT perpendicular to the rotor axis and up to 15 mT parallel to the rotor axis seem to be the upper limit for the use of TMPs in a stationary magnetic field, higher pulse loads seem to be acceptable. However, TMPs with magnetic suspension were sensitive to fields above 15 mT, causing the suspension to fail.

For W7-X it was decided to install three TMPs to each divertor chamber with a total nominal pumping speed of 6,000 l/s, connected via approx. 3.6 m and 4.3 m long tubes of 400 mm diameter, thus reaching about 4,200 l/s pumping speed for hydrogen at the plasma vessel [14].

The cryo-panels will be located directly behind the target plates in the divertor chamber with the openings pointing towards the pumping gap [15]. The restricted space and the needs for diagnostics make it necessary to divide the panels into two sections (Figure 4).
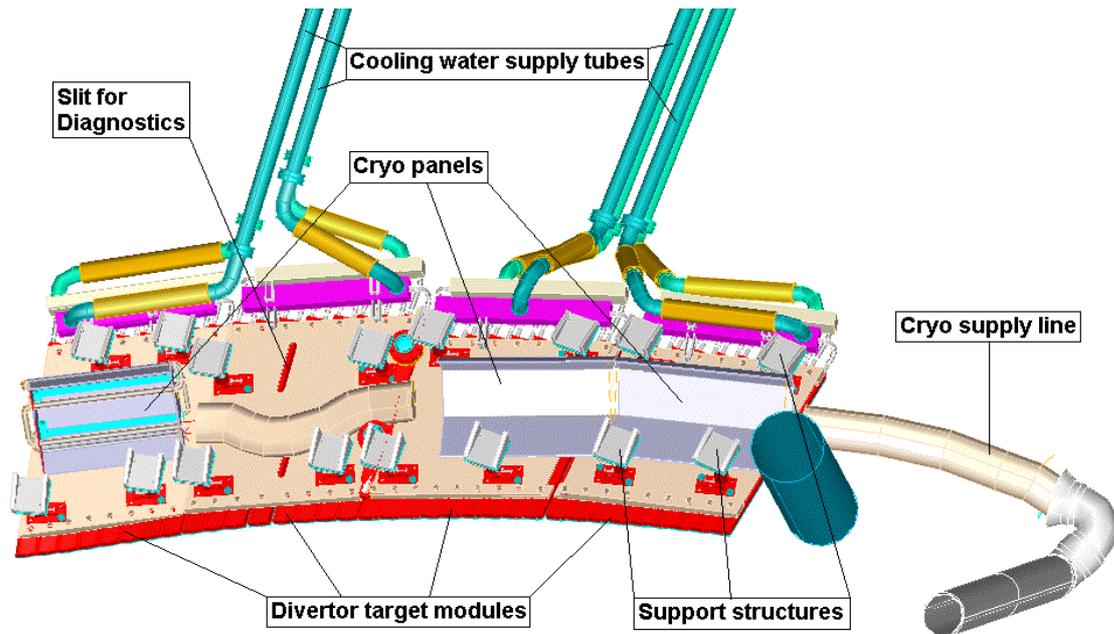
Fig. 4   Arrangement of the cryo panels behind the target modules in the divertor chamber

According to the various experimental scenarios sufficient pumping speed will be provided along the toroidal extension of the divertor chamber. However, the actual assumptions of the radiation load that enters the divertor chamber through the pumping gap, will make it necessary to install additional water-cooled chevron-baffles that suppress the efficiency of pumping. With the present design more than 10,000 l/s will be reached with a capacity of two hours pumping at a pressure of 10^{-3} mbar hydrogen. This would be enough for an experimental day, giving the possibility to regenerate the panels overnight.

Overall, the ten divertor chambers will be pumped with approximately 150,000 l/s - including both the cryo-panels and the TMPs.

Summary

The choice of the combination of CFC NB31 and CuCrZr for the target elements with the higher heat removal capacity allowed to increase the angle of incidence of the incoming particles. Thus the total wetted area of the target plates can be reduced without constraints to the experimental flexibility. Self-consistent calculations with the EMC3-EIRENE code confirm the assumptions made earlier concerning the geometry of the pumping gap. The turbomolecular pumps were tested in magnetic stray fields, their arrangement was fixed. The redesign of the cryo panels due to the new arrangement of the target plates and additional water cooling baffle is under way.

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