ELSEVIER
Journal of Nuclear Materials 313–316 (2003) 1298–1303
journal of nuclear materials
www.elsevier.com/locate/jnucmat

# Neutral particle modelling and particle exhaust in the Wendelstein 7-X stellarator

H. Grote [a,*], J. Kisslinger [b], H. Renner [a], J. Boscary [a], H. Greuner [b], F.W. Hoffmann [a], B. Mendelevitch [b]

[a] *Max-Planck-Institut für Plasmaphysik, Euratom Association Teilinstitut Greifswald, Wendelsteinstrasse 1, D-17491 Greifswald, Germany*
[b] *Max-Planck-Institut für Plasmaphysik, Euratom Association, D-85745 Garching, Boltzmannstrasse 2, Germany*

Received 27 May 2002; accepted 17 September 2002

**Abstract**

The divertor and the pumping system of Wendelstein 7-X is designed for stationary operation at various modes of operation. Maximum fluxes up to $10^{24}$ electron–ion-pairs/s are expected at the targets. Various cases of plasma–wall interaction have to be considered: at low densities convective power losses and proceeding to higher densities a high recycling mode, including detachment dominated by radiation. External fluxes (NBI, gas puffing and pellet injection) up to $10^{22}$ particles/s have to be pumped. The geometry of the target plates, the installation of additional baffle plates and the position of the pumping gap were optimised on the basis of numerical studies with the 3D neutral particle code EIRENE. For particle exhaust turbomolecular pumps (TMPs) and cryo-panels will be installed. Taking in account the capabilities of the TMP in the magnetic stray field an effective pumping speed for $H_2$ of 4200 l/s at one divertor box will be reached. Including the cryo-panels integrated inside the divertor boxes a total pumping speed of up to 200 000 l/s will be provided.


*PACS:* 52.25.Ya
*Keywords:* EIRENE code; Stellarator; Divertor; Neutrals; Pumping

## 1. Introduction

The **HELI**cal **A**dvanced **S**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 in demonstrating 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. The target plates have to follow a complex 3-D geometry as the islands are winding helical around the confinement region.

For W7-X an open divertor configuration was chosen as a first approach to match the whole operational range

* Corresponding author. Tel.: +49-3834 88 2767; fax: +49-3834 88 2709.
*E-mail address:* heinz.grote@ipp.mpg.de (H. Grote).

0022-3115/03/$ - see front matter 
PII: S0022-3115(02)01503-9

of the rotational transform and beta values. Two divertor boxes are arranged in a mirror-symmetry above and below the helical axis in each of the five field periods. They 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 [5].

In this paper we discuss the modelling of the behaviour of the neutral particles aiming at an optimal layout of the divertor structures and the pumping gap as well as an effective particle exhaust by turbomolecular pumps (TMPs) and cryo-panels. The design of these technical systems is described including tests of the working capabilities of the TMP in a stationary magnetic field.

## 2. Modelling of neutral particles

The neutral gas transport was studied using the Monte-Carlo code EIRENE [6]. Its geometrical part was specially adapted to the complex 3-D structure of the magnetic surfaces of W7-X including the islands at the edge. Stand-alone runs were performed with varying plasma parameters as input parameters [4,7]. The intersection pattern of the magnetic field lines with the divertor target plates – derived from SOL-modelling – served as sources for the neutrals. The main parameters during the investigations appear to be the variation of fluxes from the plasma. These are modified by the confinement properties and external sources of heat and particles, and the neutral pressure inside the different divertor boxes. The neutral pressure and the localisation of sources for charged particles close to the divertor have been calculated. One of the aims of W7-X is to operate in a high recycling regime with low plasma temperatures on the target plates and good screening of the confinement region from impurities. Maximum fluxes up to $10^{24}$ electron–ion pairs per second associated with a power source of 10 MW are expected at the targets with temperatures of 10 eV (Table 1). The particle flux across the last closed magnetic surface is estimated to be several $10^{22}$ particles per second depending on the density range and the confinement properties. External fluxes by NBI, gas puffing and pellet injection in a range up to $10^{22}$ particles per second will be applied for additional heating and control of the density profiles. Fig. 1 gives an overview of a possible recycling scheme.

The density of neutrals in the vessel was calculated assuming the plasma parameters at the separatrix to be $T_e = 70$ eV, $n_e = 2.5 \times 10^{13}$ cm$^{-3}$ and a particle flux to the target plates of $\Gamma = 6 \times 10^{23}$ s$^{-1}$. Fig. 2 shows the effect of the installation of baffle plates that effectively prevent the outstream of neutrals into the main plasma chamber. The density in the divertor box ranges up to several $10^{13}$ cm$^{-3}$. At room temperature $2.6 \times 10^{13}$ cm$^{-3}$ correspond to a pressure of $10^{-3}$ mbar – a value measured in tokamak divertors as well as in the recent divertor experiments at the stellarator W7-AS [8].

The ionisation rates were calculated depending on the boundary densities. For the case with baffles the

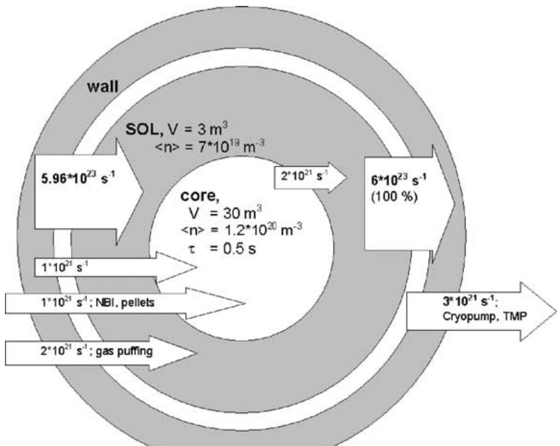


Fig. 1. Particle recycling scenario with regard to internal and external fluxes indicating the necessities for pumping in a stationary regime.

Table 1
Power and particle fluxes for the Wendelstein 7-X experiment

| | |
|---|---|
| Power, stationary | 10 MW |
| Peak power | 20 MW for period of 10 s |
| *Particle flux (external source)* | |
| NBI | $\Gamma_{NBI} < 10^{21}$ s$^{-1}$ |
| Gas puffing | $\Gamma_{GP} < 10^{22}$ s$^{-1}$ |
| Pellet injection | $\Gamma_{PI} < 10^{22}$ s$^{-1}$ |
| *Particle flux (internal source)* | |
| $\tau_p \sim 0.5$ s for $N_{max} = 10^{22}$ | $\Gamma < 2 \times 10^{22}$ s$^{-1}$ |
| Estimate of maximum fluxes related to the input power of 10 MW: | $\Gamma < 8 \times 10^{23}$ s$^{-1}$ |
| (convective power to targets per electron–ion pair: $P_d = Y\Gamma kT_d$ ; with $Y = 8$ and $kT_d = 10$ eV) | |

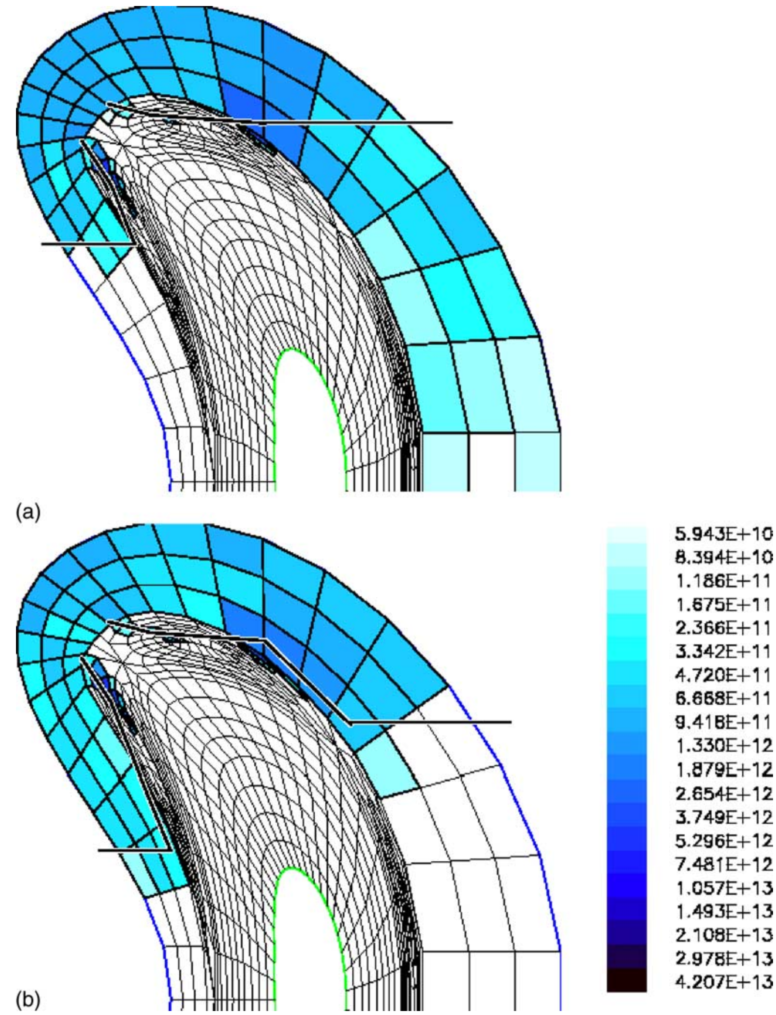


Fig. 2. Neutral particle distribution ($n_{\mathrm{H}}$ in cm$^{-3}$) in one toroidal cross-section (upper half of symmetry plane $\varphi = 0°$): (a) without the installation of a baffle at the divertor box; (b) the effect of compression of neutral particles inside the divertor box due to a changed geometry including a baffle is clearly seen.

ionisation is highly concentrated at the divertor. High ionisation rates are found at the target plates as seen in Fig. 3. The particle generation appears localised close to the interaction area of the plasma flow at the targets and an effective screening of the confinement area can be established at relatively low plasma densities. Two cases are shown with $n = 1 \times 10^{12}$ cm$^{-3}$ (Fig. 3(a)) and $n = 2.5 \times 10^{13}$ cm$^{-3}$ (Fig. 3(b)). To give a measure for the particle gain in the SOL and their screening property of the confinement region, the ratio of ionisation rates outside the last closed magnetic surface to the total ionisation rate is plotted vs. the SOL-density in Fig. 4 (other parameters as for Fig. 2).

The parameter studies resulted in an optimised design of the target plates, baffles and pumping gaps. The targets are located in the regions where the width of the islands reaches its maximum size, thus preventing neutrals to penetrate through the islands into the main confinement space. The toroidal extension of the targets covers the intersection pattern of the whole operational range of the rotational transform (5/6–5/4). A nearly constant angle of intersection (1–3°) of the magnetic field lines with the highly loaded areas keep the power density within the technical constraints of 10 MW/m$^2$. The additional baffle plates reduce the neutral particle density in the main plasma chamber and minimise the interaction of high energetic particles with the wall. The area of particle recycling is located near the pumping gaps providing an efficient particle exhaust by the pumps.

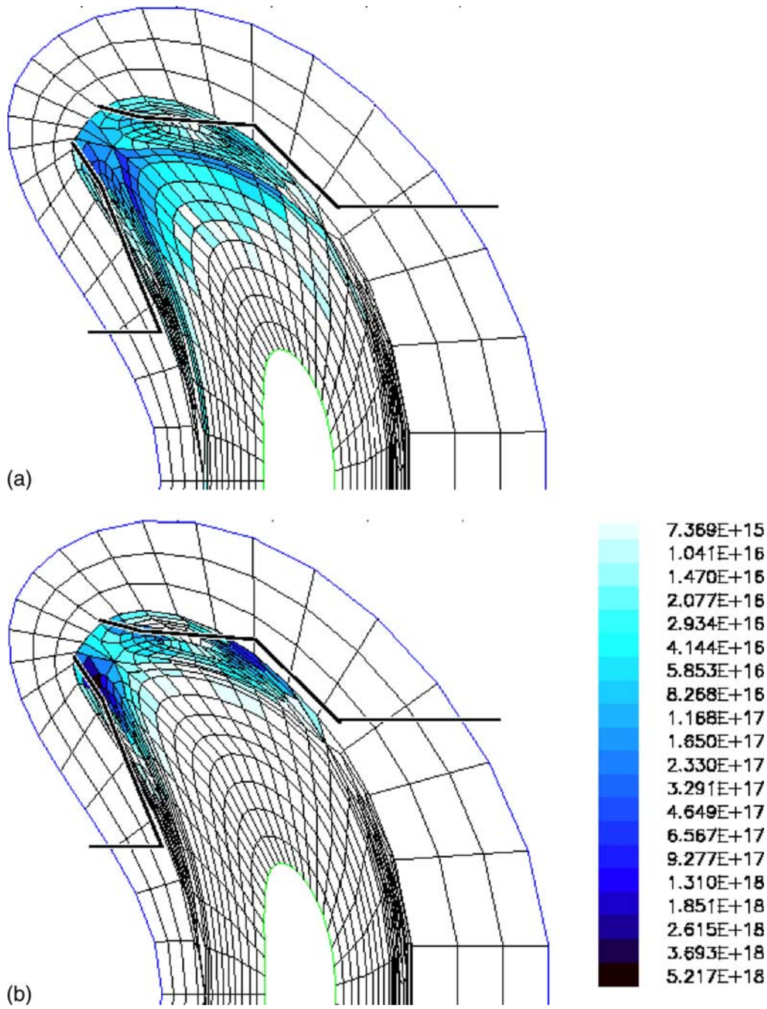


Fig. 3. Local ionisation rate ($dn_H/dt$ in $cm^{-3}\,s^{-1}$) for two SOL-densities: (a) $n = 1 \times 10^{12}$ $cm^{-3}$; (b) $n = 2.5 \times 10^{13}$ $cm^{-3}$.

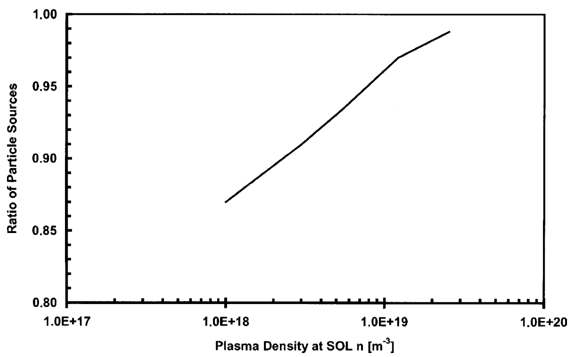


Fig. 4. Screening effect of the boundary: ratio of ionisation rate outside the LCMS to total ionisation rate in Hydrogen. Case with baffles.

## 3. Particle exhaust

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

The divertor boxes are 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 installed at each of the 10 divertor boxes and 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 10 backing pump blocks – two-stage systems with 1000 $m^3$/h roots-pumps and 65 $m^3$/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. Here the magnetic stray field components induce eddy currents in the rotor that tend to reduce its speed. However, the temperature of operation of the rotor is limited to about 120 °C due to a decrease of its strength at higher temperatures and its thermal expansion [9]. Consequently the positioning of the TMPs will be a compromise with respect to the effective pumping speed in the divertor box and the value of the magnetic stray field. TMPs with a rotor made of ceramic were developed for use in a magnetic field [10,11], but are not yet available commercially.

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. Variable positions of the TMPs with respect to the magnetic field lines were investigated (perpendicular to the rotor axis up to parallel to the rotor axis).

A gas load up to 5 mbar l/s hydrogen could be introduced to the high vacuum side of the TMP to simulate the experimental conditions at W7-X. The pressure and the temperature of the rotor were measured as well as the output parameters of the power supplies.

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. 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 with a total nominal pumping speed of 6000 l/s, connected via approx. 3.6 and 4.3 m long tubes of 400 mm diameter to each divertor box, thus reaching about 4200 l/s pumping speed for hydrogen at the plasma vessel (Fig. 5).

The cryo-panels will be located directly behind the target plates in the divertor box with the openings pointing towards the pumping gap [12]. The restricted

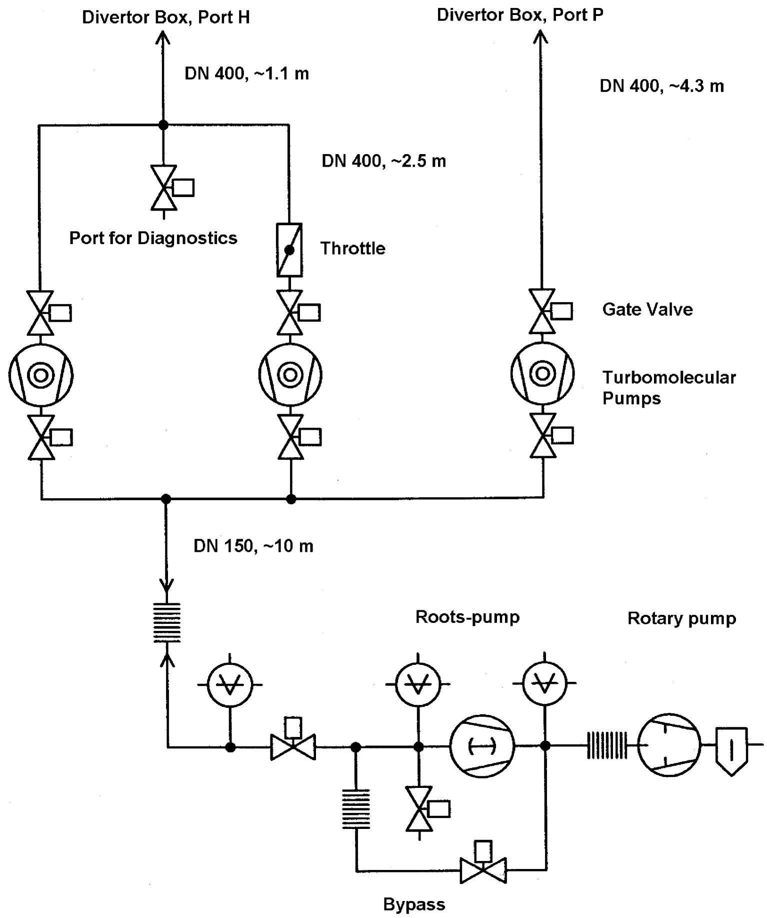


Fig. 5. Scheme of the turbomolecular pumping system for one divertor box. The pumping ports are named AEH and AEP. The throttle will be used to adjust the pumping speeds of the different divertor boxes or to reduce the pumping speed for experimental purposes.

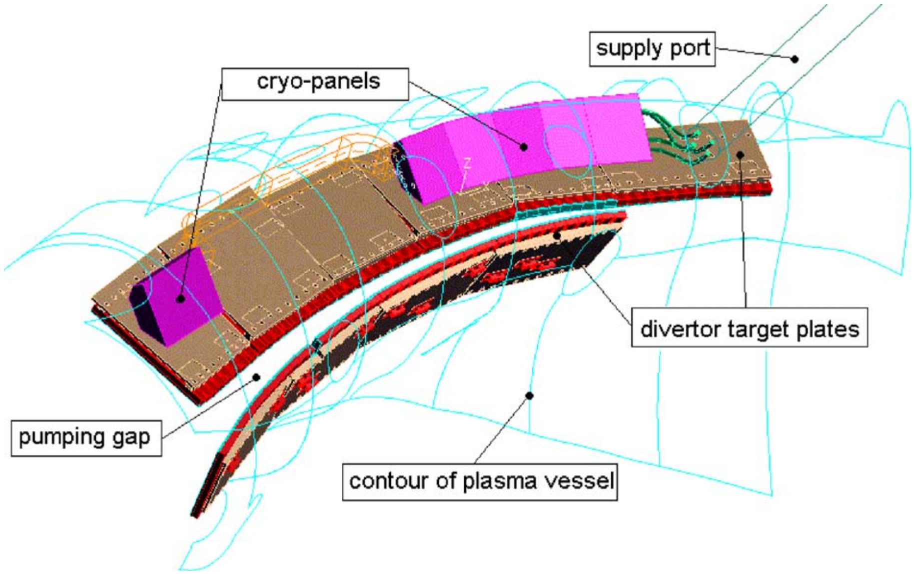


Fig. 6. CAD-drawing of the location of the cryo-panels in the divertor box. The chevron baffles (80 K) point towards the pumping gap between the horizontal and vertical target plates. The construction space is limited by the plasma vessel (grid lines) and diagnostic needs between the two individual panels.

space and the needs for diagnostics make it necessary to divide the panels into two sections (Fig. 6). According to the various experimental scenarios sufficient pumping speed will be provided along the toroidal extension of the divertor box. With the present design more than 20 000 l/s could be reached with a capacity of 2 h 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. However, the actual assumptions of the radiation load that enters the divertor box through the pumping gap, could make it necessary to install additional chevron baffles that suppress the efficiency of pumping.

Overall, the 10 divertor boxes will be pumped with approximately 200 000 l/s – including both the cryo-panels and the TMPs.

## 4. Summary

The neutral particle balance was evaluated with the 3D Monte-Carlo code EIRENE. The geometry and location of the target plates, baffles and pumping gaps was optimised to ensure efficient particle exhaust. The TMPs were tested concerning their working capabilities in a stationary magnetic field, the pumping ducts and the positioning of the TMPs were fixed. The cryo-panels, integrated into the divertor boxes, were designed with respect to the restricted space and needs for diagnostics.

## References

[1] J. Nührenberg, R. Zille, Phys. Lett. A 114 (1986) 129.
[2] J. Nührenberg, R. Zille, Phys. Lett. A 129 (1988) 113.
[3] G. Grieger et al., Phys. Fluids B 4 (1992) 2081.
[4] C.D. Beidler et al., Proceedings of the 20th EPS Conference on Controlled Fusion and Plasma Physics, Lisbon 1993, ECA 17C Eur. Phys. Soc., Geneva 1993, part II, p. 787.
[5] H. Renner et al., Nucl. Fusion 40 (2000) 1083.
[6] D. Reiter, Jülich Report 1947 (Jülich 1984).
[7] J. Kisslinger et al., Proceedings of the 21st EPS Conference on Controlled Fusion and Plasma Physics, Montpellier 1994, ECA 18B Eur. Phys. Soc., Geneva 1994, part I, p. 368.
[8] P. Grigull et al., Plasma Phys. Control. Fusion 43 (2001) A175.
[9] W. Becker, J. Henning, J. Vac. Sci. Technol. 15 (1978) 768.
[10] Y. Murakami et al., J. Vac. Sci. Technol. A 5 (1987) 2599.
[11] K. Ioki et al., Fusion Eng. Des. 10 (1989) 223.
[12] J.C. Boissin, IPP Internal Report, April 2002.