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Divertor helium pumping in TdeV-96 under various conditions

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Abstract

In this paper, we report on the effects of density, divertor geometry and ECRH heating on divertor pressure and helium enrichment. Low, medium and high (semi-detached) densities were investigated with outboard pumping (OB) and private region pumping (PR). For OH discharges, density and geometry effects are compared with B2-EIRENE simulations. There is general agreement with experiments, except for the high density, private region pumping case where the experimental enrichment is lower than predicted. We studied the effect of H- and L-modes on He pumping. L-modes gave the highest divertor pressures and enrichment. H-modes did not affect appreciably the total pressure but the enrichment decreased. Finally, the effects of baffling, biasing and divertor fuelling are discussed; and a comparison is made between a two-reservoir and four-reservoir model for particle balance. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: B2-EIRENE; Divertor pumping; Helium exhaust; Tokamak de Varennes

1. Introduction

Helium exhaust is an important aspect of ITER design. The requirements are with the global confinement time of helium ($\tau^*_{\mathrm{p,He}} < 10\tau_{\mathrm{E}}$) to reach ignition and with its enrichment factor ($\eta_{\mathrm{He}} > 0.2$) for technical and cost reasons. The absolute values of enrichment and global confinement times obtained on TdeV ($R = 0.83$ m, $I_{\mathrm{p}} = 220$ kA, $B_{\mathrm{T}} = 1.96$ T) may not apply directly to a much larger machine and may require some scaling. However the trends obtained as a function of parameters such as density, outboard/private region pumping, OH/H/L modes and by comparison with simulation codes give valuable direction and information for future experiments.

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2. Experimental

For these experiments, pumping is performed in the active divertor only, using a commercial pump efficient for both deuterium and helium. Helium is puffed in the main chamber early in the discharge and its decay time constant (τ^*_{p}) is measured from a He II monitor looking in the main plasma (Fig. 1). When the walls are cleaned with glow discharge in helium, a few low-density shots must follow in order to reduce the helium content of the plasma. The same sequence is repeated without helium injection in order to subtract the helium background. With this sequence, the pumping of the tiles on helium is negligible at medium and high densities, but must nevertheless be taken into account for the low density shots. Using a two-reservoir model, τ^*_{p} is related to He compression (C_{He}) from which we can obtain the enrichment (η):

$$C_{\mathrm{He}} = \frac{n_{\mathrm{d,He}}}{\langle n_{\mathrm{p,He}}\rangle} = \frac{V_{\mathrm{p}}}{V_{\mathrm{d}}}\left(\frac{\tau^*_{\mathrm{p}}}{\tau_{\mathrm{ex}}} - 1\right)^{-1},$$

$$\eta = \frac{C_{\mathrm{He}}}{n_{\mathrm{d,D}}/\langle n_{\mathrm{p,D}}\rangle}$$

where $n_{\mathrm{d,He}}$ and $n_{\mathrm{p,He}}$ are the helium densities in the divertor plenum and main plasma, $n_{\mathrm{p,D}}$ and $n_{\mathrm{d,D}}$ are the

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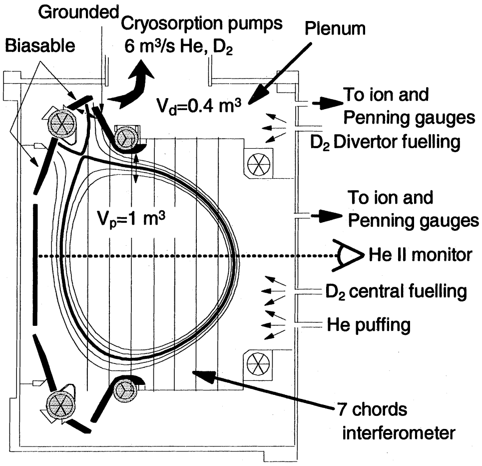

Fig. 1. TdeV-96: The separatrix can be positioned on the divertor plate for outboard pumping (as shown) or for private region pumping. The throat can also be independently adjusted. Vacuum gauges are located in the divertor plenum and in the main chamber.

deuterium densities in the divertor plenum and main plasma, V_d and V_p are the divertor plenum and main plasma volumes, and τ_{ex} is the pumping time constant of the divertor plenum (Fig. 1). Subsequently a four-reservoir model was developed and comparison is discussed at the end of this paper.

The plasma mean electron density is obtained from a 7-chord interferometer, and the partial pressures of He and deuterium in the divertor and main chamber were measured with modified Penning gauges [1]. The quantity of He puffed is adjusted to have 5–7% helium content in the main plasma as deduced from its partial pressure in the divertor and from its measured compression.

3. B2-EIRENE simulations

The simulations were performed with the B2-EIRENE code package [2] for three densities (0.5, 0.9, and 1.6×10^{19} m^{-3}) at the core-SOL boundary. The temperature at the core-SOL boundary was adjusted to give a power input of approximately 100 kW into the scrape-off layer for transport coefficients of $D = 0.4$ m^2/s and $\chi = 3$ D. The carbon (2%) and helium (5%) concentrations were imposed at the same boundary. Both configurations, outboard and private region, pumping were investigated. More complete details of the simulation are described in Ref. [3] where we compared electron density and temperature at the divertor plate as well as the D_α emission near the plate. Reasonable agreement was found.

4. Density and magnetic geometry effect

Experimental values of enrichment and divertor pressures are shown in Fig. 2 for three densities and three magnetic geometries: private region pumping (PR) and outboard pumping (OB) with the separatrix two flux lines away from the slot and one flux line away from the slot. A flux line corresponds to 5% of the poloidal flux at the separatrix and gives a separation of about 2 cm between flux lines on the divertor target plate. Simulated values are compared. $\mathbf{B} \times \nabla\mathbf{B}$ was pointing away from the X-point for those experiments. It is observed that geometry has a strong effect on enrichment at low density and that increasing the density decreases enrichment, especially in the PR configuration where its experimental value varies from $\eta = 0.6$ at low density (attached) to $\eta = 0.25$ at high density (semi-detached). Enrichment in the OB configuration is around 0.3 for the highest densities investigated.

In experiment and in simulation, the divertor plenum pressure rises faster than the core plasma density (as $\langle n \rangle^{1.7}$ in experiment, as $n_{sep}^{1.3}$ in simulation), and is lower for pumping in the private region than for outboard pumping (~0.6). Helium enrichment does not vary

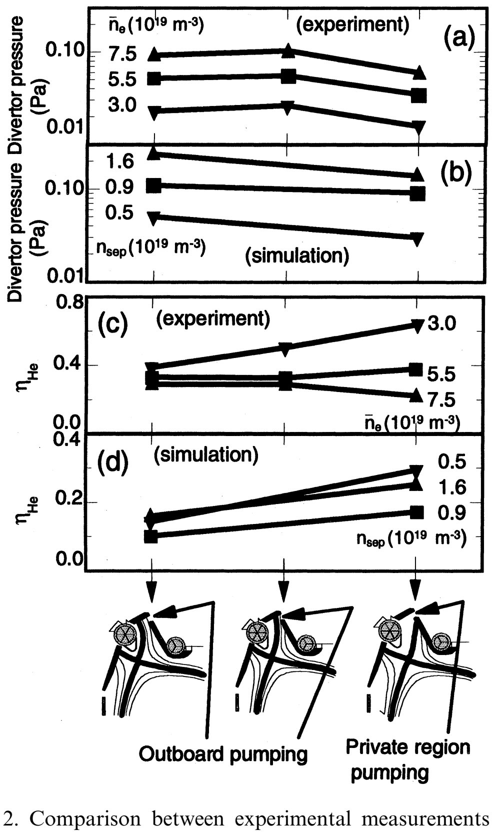

Fig. 2. Comparison between experimental measurements and B2-EIRENE simulations for (a), (b) divertor pressure and (c), (d) He enrichment.

appreciably with density for the outboard pumping geometry in the experiment nor in the simulation. For private region pumping, as the density is raised from low to medium values, the helium enrichment drops in both experiment and simulation. However, the simulation predicts an increase of enrichment at the highest density, a tendency that is not observed in the experiment. The numerical values for pressure and helium enrichment obtained in the simulation are, respectively, twice and one-half those experimentally observed. These discrepancies may be due in part to the imperfect treatment of the pumping slot in the simulation. In addition, adjustment of the transport coefficients and of the radiated power is surely required to better reproduce the profile shapes and temperature values near the plate.

Overall, the tendencies observed in the experiment are well reproduced by the simulation, especially for low and medium densities.

5. Comparison of OH-, H- and L-modes

Steady state H-modes are routinely obtained on TdeV, mainly with the ECRH system. With the ECRH power initially limited to 0.5 MW, the ELMs remain of type-3. Experiments were performed with $\mathbf{B} \times \nabla \mathbf{B}$ pointing towards the X-point in order to favor the H-mode. Previous He pumping experiments presented here were performed with the opposite toroidal magnetic field.

Fig. 3 shows the divertor pressure, He partial pressure and enrichment obtained with and without EC heating with OB and PR pumping geometries. OH results are also shown. H-modes appear to have only a small effect on divertor pressures. The increased particle confinement obtained from the edge barrier is cancelled by the loss of confinement effect due to strong heating; however the enrichment is seen to decrease by about 25%. On the other hand, the L-mode doubled the divertor pressures and provided a 25% increase in enrichment.

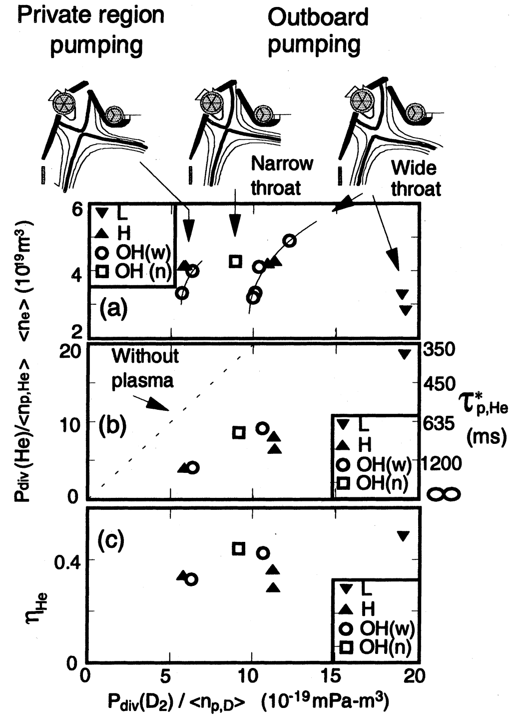

Fig. 3. Results for private region pumping, outboard pumping and outboard pumping with a narrow throat are shown for OH-, H- and L-modes. As a function of divertor deuterium pressure, (a) shows the plasma density, (b) the divertor helium pressure and the helium global confinement time and (c) the helium enrichment. Pressures are normalized to the species plasma density.

6. Effects of divertor fuelling, biasing and divertor baffling

Divertor fuelling increased the deuterium partial pressure in the plenum but did not affect He pumping significantly as seen in Fig. 4. With 150 V negative biasing, such that $\mathbf{E} \times \mathbf{B}$ points towards the outer divertor, and at high density, the divertor plenum pressure increased by 120% (Fig. 5) while the enrichment increased by about 50%, rising from 0.31 to 0.48. Those combined effects gave a helium throughput that increased 3.3 times.

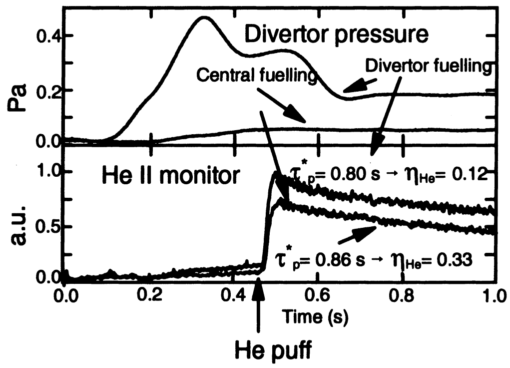

Fig. 4. Top: divertor pressure with and without divertor fuelling. Bottom: He II signals and their associated decay time.

In one OH experiment, the throat of the divertor was decreased from 2 to 1 SOL width. We observed a 15% decrease in divertor deuterium pressure (Fig. 3) and a 20% increase of D_α emission near the throat, indicating that the ionic flow to the divertor is reduced while recycling is increased near the entrance. The He enrichment is also increased by 7% but this may not be significant.

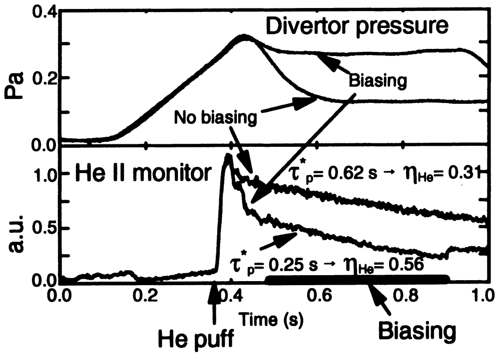

Fig. 5. −150 V is applied between the quasi-horizontal plate and the ground. Top: effect of biasing on the divertor pressure. Bottom: effect of biasing on the He II signals and their associated time constants.

7. Four-reservoir model

The wall conditions are changing from shot to shot as the walls pump or release deuterium and helium. They are influenced by boronization, glow discharge cleaning, disruptions and many other factors. With deuterium, it is relatively easy to perform a particle balance and deduce flow in and out of the walls from partial pressures, gas fuelling and interferometric measurements. Due to the absence of a neutral beam diagnostics to monitor He in the central plasma, the particle balance for helium is a little more complicated. Here, we expanded to a four-reservoir model to account for the main plasma, divertor neutrals, main chamber neutrals and walls (Fig. 6), with, respectively, N_p, N_d, N_{edge}, N_w particles. The SOL and divertor plasma are included as a single recycling region with N_R particles.

Since this last region contains only a small fraction (∼3%) of the total particle content, we assume $N_R = dN_R/dt = 0$. We define Γ_R as the total flux entering that recycling region with f_d and f_w the fractions of Γ_R entering the divertor plenum and the wall, respectively. Γ_{edge} is the flux from the plasma to the edge, and τ_p, τ_d, τ_w, τ_{edge} are the confinement times in each volume. Typically, $\tau_p = 20$ ms, $\tau_d = 35$ ms, $\tau_{edge} = 4$ ms and τ_w is several seconds for deuterium. The values used for He are the same except for $\tau_{edge} = 2$ ms. The two populations (D and He) are only linked through the plasma density: $\langle n_e \rangle = \langle n_d \rangle + 2\langle n_{He} \rangle$. The differential equations are solved as a function of time and results compared with the experimental measurements P_{div}(tot), P_{div}(He) P_{edge}(tot) and P_{edge}(He).

Calibrated H_α chords in the main plasma can be related to the molecular flux entering the plasma [4] and to the edge pressure. Therefore, an H_α signal was used as a deuterium pressure measurement in the edge. In the same manner, the He II signal could be used to obtain He partial pressure measurement in the edge. In our experiment this signal was used without absolute calibration.

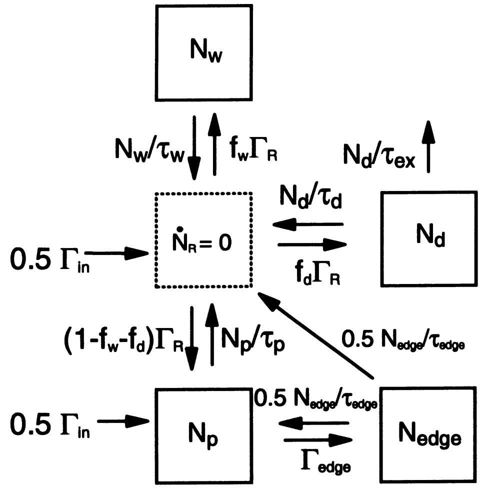

Fig. 6. Four-reservoir model taking into account the plasma, the divertor plenum, the edge neutrals and the walls. Γ_R is the sum of all the fluxes entering the recycling region. Γ_{in} is the external fuelling and N_d/τ_{ex} is the flux of particles going to the pump.

τ_p, τ_d, τ_n and τ_{ex} are deduced from separate experiments and are imposed in this model. For a series of four shots (with/without He, with/without pumps) τ_w, f_d, f_w and Γ_{edge} are adjusted only once. For each shot the initial number of particles in the wall is adjusted. Fig. 7 shows experimental data and the best fit from the four-reservoir model for an OH shot with private region pumping. There is general agreement between the two models. The four-reservoir model results give, on an average, 15% lower He global confinement times than

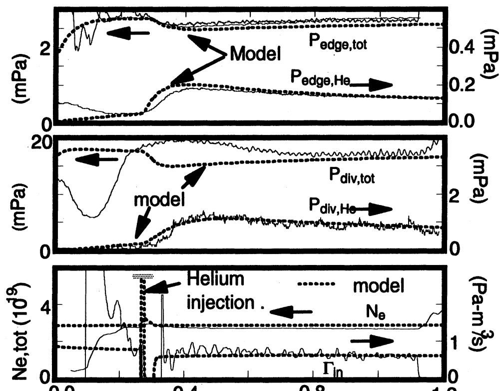

Fig. 7. Comparison between the output of the four-reservoir model and real signals. The total and He pressures in the edge and in the divertor are shown in the top two graphs. The bottom graph shows the plasma electron density and the fuelling for deuterium and helium.

deduced from τ_p^* and the two-reservoir model. Background helium in the edge, omitted by the first model, is the main cause for the difference. Walls pumping helium immediately after the He puff and releasing the pumped He later in the discharge is less important than anticipated and shows that the two-reservoir model was taking into account the walls effect properly. In some cases, helium will outgas from the cryosorption pumps during ECRH injection, giving less reproducible helium background than in OH mode.

8. Conclusion

Deuterium retention and helium enrichment were studied as a function of geometry and density. For PR geometry, the total pressure was 40% lower than for OB. It is found experimentally for both geometries that deuterium retention in the divertor increased with density while enrichment decreased and results were not affected by detachment. This density effect on enrichment is three times more important for PR geometry than for OB. The most interesting configuration for ITER: high density with PR geometry gave us an enrichment of 0.25, which is less than half the value obtained at low density. Compared to the OB geometry at high density, the helium throughput has dropped by 50%. B2-EIRENE simulations gave the same geometry and density dependence for divertor pressure and enrichment as in the experiment, except for the high-density cases. There, the simulation indicates enrichments comparable to the low-density cases for PR and OB geometries, in contrast with the experimental results. As explained in Ref. [3], the simulation may represent higher densities than experimentally investigated. Therefore, at higher densities and with more detached plasmas, we would expect the experimental enrichment to start increasing, according to the simulation.

H-modes did not affect very much the divertor pressure but decreased the enrichment by 25% with OB geometry. L-mode about doubled the divertor pressure and increased the enrichment by 25% with OB geometry. PR geometry showed no change in pressure nor in enrichment with an H-mode. For maximum helium throughput, the best scenario with ECRH would be an L-mode with outboard pumping.

Divertor biasing increased the divertor pressure by 120% and the enrichment by 50%, therefore increasing the helium throughput by 230%. Divertor fuelling did increase the deuterium pressure but did not affect the helium pumping time and therefore reduces the enrichment factor. Reducing the baffling from 2 to 1 SOL width, reduced the divertor pressure by 15% but did not significantly affect the He enrichment. Finally, neglecting to treat the edge and the walls as reservoirs contributed to the underestimation of the enrichment factor by only 15% in most cases. Therefore it is appropriate to continue using the simplistic two-reservoir model for helium.

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