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PARTICLE EXHAUST OF HELIUM PLASMAS WITH ACTIVELY COOLED OUTBOARD PUMP LIMITER ON TORE SUPRA

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ABSTRACT

The superconducting tokamak Tore Supra was designed for long-pulse (30-s) high input power operation. Here observations on the particle-handling characteristics of the actively cooled modular outboard pump limiter (OPL) are presented for helium discharges. The important experimental result was that a modest pumping speed (1 m^3/s) of the OPL turbomolecular pump (TMP) provided background helium exhaust. This result came about due to a well-conditioned vessel wall with helium discharges that caused no wall outgasing. The particle accountability in these helium discharges was excellent, and the well-conditioned wall did not play a significant role in the particle balance. The helium density control, 25% density drop with OPL exhaust efficiency of ~1%, was possible with TMP although this may not be the case with reactive gases such as deuterium. The observed quadratic increase of the OPL neutral pressure with helium density was consistent with an improvement of the particle control with increasing plasma density.

1. INTRODUCTION

Steady-state operation of magnetic fusion plasmas requires active control of both heat and particles. The superconducting tokamak Tore Supra was designed for long-pulse (30-s) high heating power discharges. Actively cooled plasma facing components, such as modular pump limiters, are used for power-handling and particle exhaust. This paper reports experimental observations on the particle-handling characteristics of the Tore Supra actively cooled modular outboard pump limiter (OPL) [1]. The important experimental result was that a modest pumping speed (1 m^3/s) of the OPL turbomolecular pump (TMP) provided the background helium pumping even though the particle control with pump limiters generally requires a pumping speed at least close to the neutral backflow conductance of the pump limiter throat, which is ~5 m^3/s for the OPL. This result came about due to a well-conditioned vessel wall with helium discharges that caused no wall outgasing.

2. PUMP LIMITER CHARACTERISTICS AND DIAGNOSTICS

For long-pulse operation, the pump limiter head must be equipped with active cooling. The design of a pump limiter is always a compromise between a thin limiter head for high particle exhaust and a leading edge (LE) that is sufficiently recessed to be in a region of tolerable heat flux. The present active cooling technology of heat removal can handle typically 5 MW/m^2 on average and ~20 MW/m^2 maximum effectively. At the leading edge of the limiter module, the cooling channel determines the thickness of the limiter head. With this in mind, the OPL design was optimized for particle collection to control the plasma density effectively, and the two-sided collection of the scrape-off layer (SOL) ion flux is ensured by lateral throats recessed by $r_{LE} = 2.5$ cm from the last closed flux surface (LCFS) with an opening of $\Delta = 2.5$ cm (Fig. 1).

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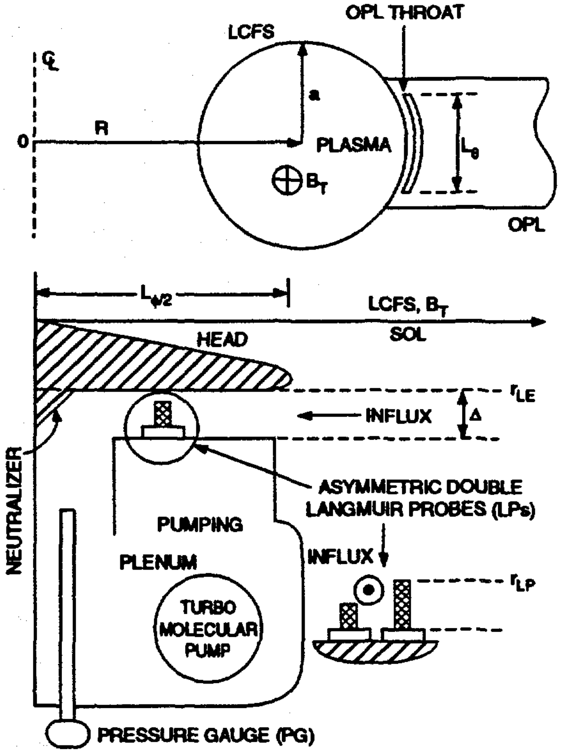

Fig. 1. Schematic of the two-sided Tore Supra OPL (only one side is shown) and its diagnostics, namely LPs and PGs. Here the dimensions are $r_{LE} = \Delta = 2.5$ cm, $L_\phi = 0.5$ m, and $L_\theta = 0.6$ m. The turbomolecular pump has a pumping speed of ~$1 m^3/s$.

The toroidal and poloidal extents of the OPL are $L_\phi = 0.5$ m and $L_\theta = 0.6$ m, respectively. The limiter head is made of cooling tubes brazed with pyrolytic graphite tiles for removing a total steady-state power load of 1.5 MW. The OPL is equipped with a titanium getter pump with a speed of ~50 m^3/s for reactive gases and a turbomolecular pump of 1 m^3/s that provides background pumping as well as pumping of nable gases like helium. The OPL diagnostics are a set of asymmetric double Langmuir probes (LPs) located on both the ion drift and the electron drift sides of the pump limiter throat entrance. The Langmuir probes are $r_{LP} = 3.3$ cm radially away from the LCFS and are used for measuring the throat electron density n_e, the temperature T_e, and the particle flux e-folding length λ_Γ.In addition, the pressure gauges (PGs) connected into both the ion drift and the electron drift sides of the pumping plenum of the module (Fig. 1) measure the neutral particle pressure p_0 resulting from the ion influx Φ_{influx} into the OPL throat.

3. EDGE PLASMA PARAMETERS AND PARTICLE COLLECTION

The OPL experiments were performed with helium plasmas to prevent wall particle saturation (the inboard limiter is made of 12-m^2 graphite tiles, which can contain 100 to 1000 times the total plasma content [2]) and the corresponding difficulties with plasma density control. During these experiments only the turbomolecular pump was activated. The discharge was initiated on the inboard limiter, later moving it to the OPL at t = 3 s after the startup, and keeping the plasma there at about $\Delta t = 10$ s during the steady-state conditions. The ohmically heated discharge parameters for this series of experiments were as follows: major radius, 2.4 m; core plasma radius, 0.725 m; toroidal magnetic field, 3.8 T; plasma current, $I_p = 1.45$ MA; and ohmic heating power, 1.45 MW. The OPL throat plasma and the pumping plenum neutral particle characteristics were measured with the Langmuir probes and the pressure gauges. Here the results are presented during the density scan, namely the line average core plasma density $\bar{n}_e = (3 \text{ to } 5) \times 10^{19}$ m^{-3} obtained using density feedback by controlling the helium injection into the discharge for compensating the exhaust of the OPL with the turbomolecular pump. In Fig. 2(a) the OPL throat n_e and in Fig 2(b) the corresponding T_e are presented as functions of $\bar{n}_e$. As expected, T_e decreases with $\bar{n}_e$, whereas n_e increases. However, there is an asymmetry between the ion drift and the electron drift sides of the OPL. This asymmetry was also observed with diagnostics of the heat deposition on the limiter head with the infrared camera and the water calorimetry measurements. The SOL characteristic scale length λ_Γ is given in Fig. 2(c), and λ_Γ slightly increases with $\bar{n}_e$. The neutral helium pressure p_0 in the OPL plenum is shown in Fig. 2(d), and p_0 increases quadratically with $\bar{n}_e$, reaching $p_0 = 3$ mTorr for $\Phi_{influx} \approx 25$ Torr-L/s at $\bar{n}_e = 5 \times 10^{19}$ m^{-3}.

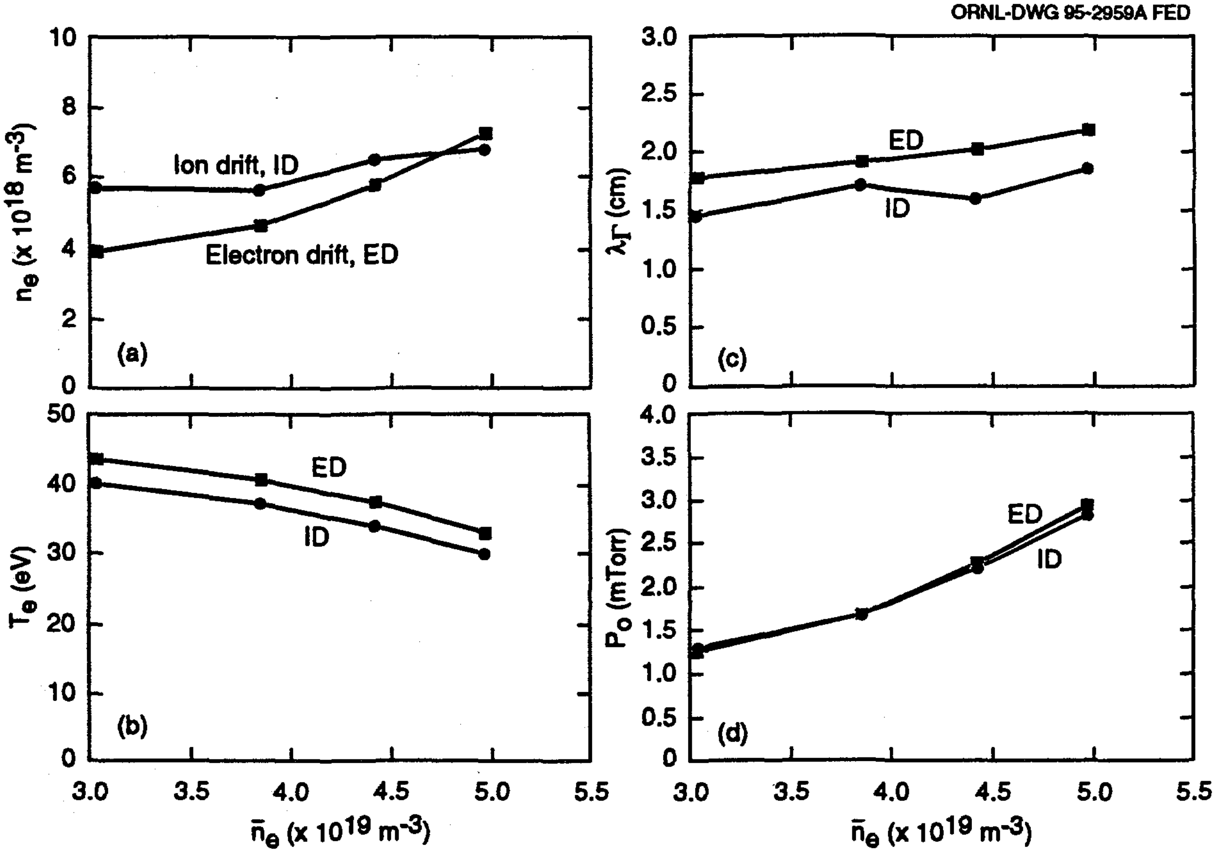

Fig. 2. Variations of (a) n_e, (b) T_e, (c) λ_Γ of OPL throat plasma, and (d) neutral pressure p_0 in pumping plenum with core plasma $\bar{n}_e$.

The quadratic increase of p_0 with $\bar{n}_e$ is similar to observations made in Tore Supra with deuterium [3,4] and also in high recycling D-III divertor plasmas [5]. To access the particle collection characteristics of the OPL, the collection efficiency $\varepsilon_{coll} = \Phi_{influx} / \Phi_{sol}$ [6] is calculated. Here $\Phi_{sol} = \Gamma_o \times L_\theta \times \lambda_\Gamma$ is the total number of SOL particles within the flux tube, defined by the OPL, $\Gamma_o = 0.5\ c_s \times n_e \times \exp(r_{LP}/\lambda_\Gamma)$ is the particle flux at the LCFS, and $c_s = (T_e/m_i)^{0.5}$ is the ion sound speed. Using the Langmuir probe results, the particle collection efficiency is estimated as $\varepsilon_{coll} = 20\%$, Fig. 3, which is consistent with the OPL design value for $r_{LE} = 2.5$ cm and $\lambda_\Gamma = 2$ cm.

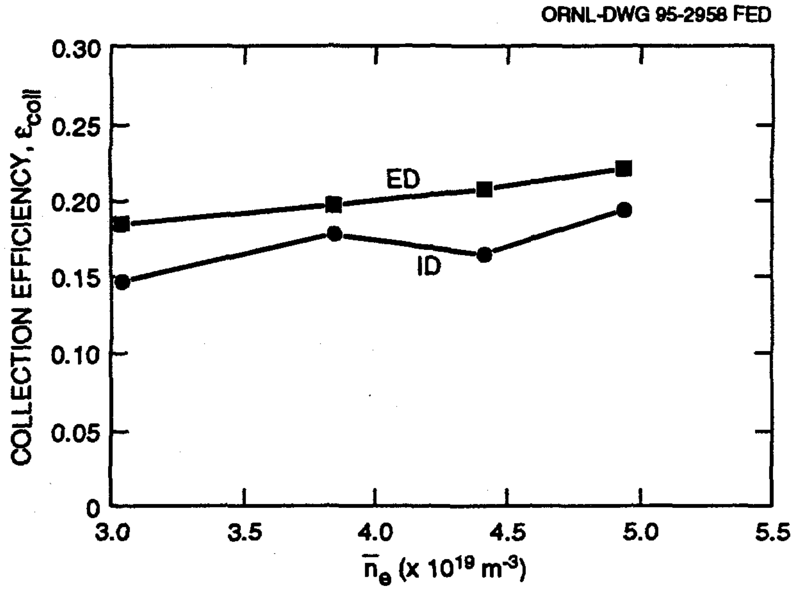

Fig. 3. Collection efficiency of the OPL core plasma $\bar{n}_e$.

4. PARTICLE BALANCE AND HELIUM EXHAUST

Using the particle conservation, the particle balance of the helium discharge is written as $\int \Phi_{inj}\, dt = \int S_{eff}\, N_L\, dt + N_e/2 + N_L\, V_L$, where Φ_{inj} is the helium injection rate, N_L is the number of helium neutrals in the OPL plenum, S_{eff} is the effective pumping speed, N_e is the total number of plasma electrons, and V_L is the volume of the OPL pumping plenum (3 m^3). Moreover, the time integration here is from the start of the discharge t = 0 to any time less than the end of the discharge (t = 13 s). Here the contribution of impurities and also any desorbed deuterium to the plasma density are ignored because these discharges followed a long series of 30 helium discharges of about 10 to 15 s; these provided a substantial helium "preconditioning" to remove surface deuterium from the vessel wall. Figure 4 shows the resulting time evolution of the particle balance. As observed, the particle balance is quite good since nearly all the particles are recovered in the discharge. Also, with helium discharges, the wall particle content is negligible and does not appear in the particle balance.

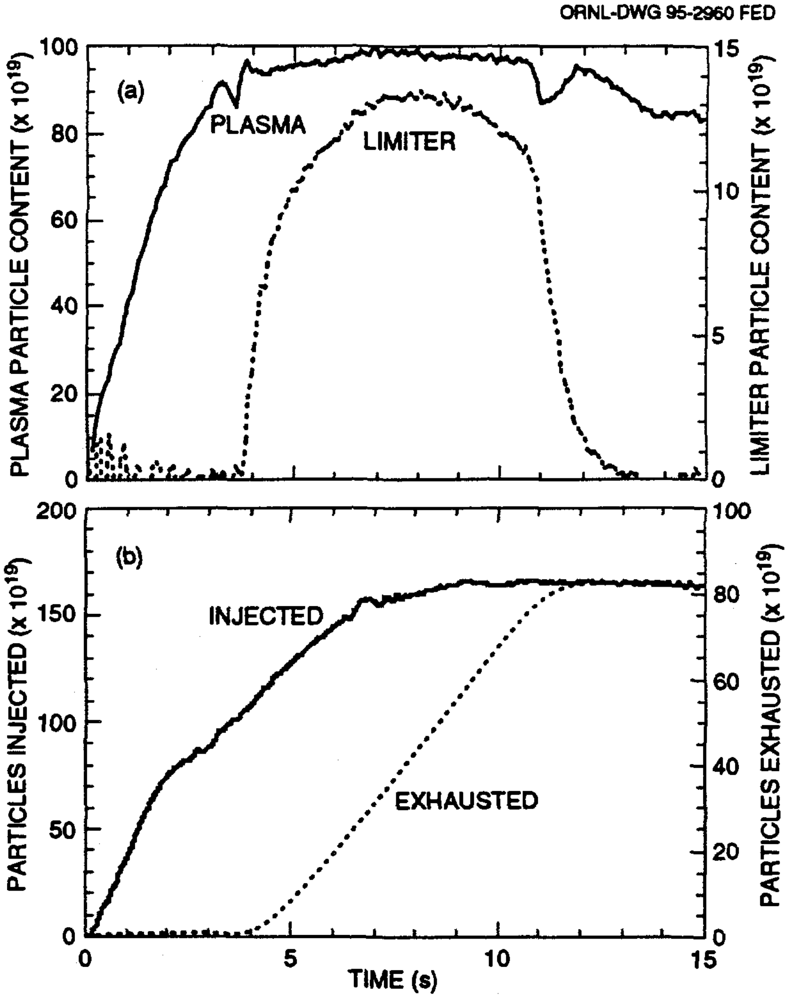

Fig. 4. Particle balance of helium discharge is well satisfied between (a) plasma and OPL plenum particle content and (b) injected and exhausted particles.

This result demonstrates that the particle balance for helium plasmas is well explained without including any effects from the wall. In other words, the wall particle content does not play a significant role in the particle balance, and the recycling coefficient is close to about 100% for helium discharges. This is not the case when the working gas is deuterium; then the wall reservoir becomes the most important contributor in the particle balance compared to the gas injection, the plasma content, the particle exhaust, and the pump limiter volume [2].

Next, the OPL particle exhaust experiment was carried out (I_p = 1.0 MA, from 2.5 to 14 s) by comparing the plasma density of two identical helium (Φ_{inj} = 0) discharges (here the global particle recycling coefficient $R_n \approx 1$) with and without the turbomolecular pump activated. Both discharges were initiated on the inboard limiter and shifted onto the OPL at t = 3 s; the time evolutions of plasma densities are shown in Fig. 5 (a). In spite of the low pumping speed of the turbomolecular pump ($S_{eff} = 1\ m^3/s$), helium exhaust was achieved at

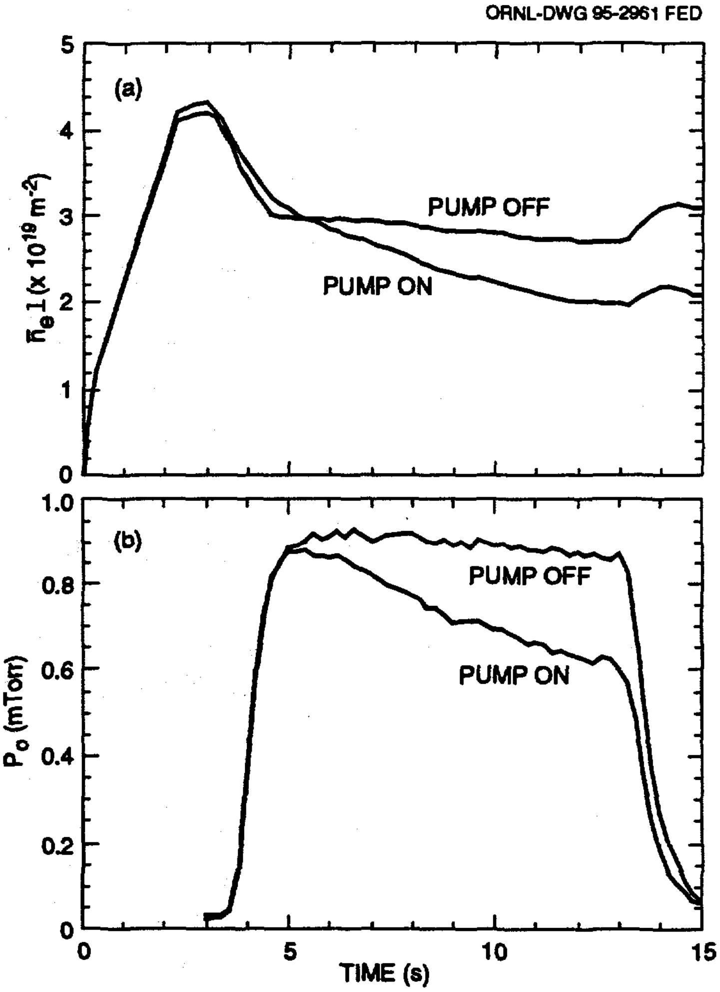

Fig. 5. Effects of OPL turbomolecular pump, 1 m^3/s (off/on): (a) core helium line density and (b) p_o of pumping plenum.

a rate of $\Phi_{exh} = p_o \times S_{eff} = 0.5$ Torr-L/s [Fig. 5 (b)]. The exhaust efficiency of the OPL is then estimated as $\varepsilon_{exh} = \Phi_{exh} / (N_e / \tau_p)$ [6], where τ_p is the global particle confinement time. From the plasma efflux $N_e/\tau_p \approx 42$ Torr-L/s (typically $\tau_p \approx 0.2$ s [2]), the exhaust efficiency becomes $\varepsilon_{exh} = 1.3\%$ for these discharges. Nevertheless, this relatively low exhaust efficiency of the OPL had a significant effect on the core density, as shown in Fig

5(a), resulting in a 25% helium plasma density ($n_e = 2 \times 10^{19}$ m^{-3}) reduction. This observation can qualitatively be explained from the general particle balance by writing $N_e = (\Phi_{inj} - dN_e / dt)\, \tau_p / (1 - R_n + \varepsilon_{exh})$, and since $R_n \approx 1$ due to well conditioned vessel wall, then relatively small values of ε_{exh} have a significant effect on the plasma density as in the experiment ($\Phi_{inj} = 0$).

5. CONCLUSIONS

Several important results from the OPL experiments are observed on the helium plasmas. First, the particle accountability in Tore Supra helium discharges is excellent for the present case. Second, the vessel wall was well conditioned and did not play a significant role in the particle balance during helium plasmas. Third, the density control in these helium discharges was possible with a modest pumping speed, 1 m^3/s, of the turbomolecular, although this may not be the case with reactive gases such as deuterium. Finally, the quadratic increase of the OPL neutral pressure with helium density indicates with an improvement of the particle control with increasing plasma density.

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