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Modeling of neutral pressure and pumping in the Tore Supra ergodic divertor and outboard pump limiter [1]

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Abstract

Active control of the core plasma density and partial depletion of the wall particle content have been achieved in experiments on Tore Supra with the plasma leaning on either the ergodic divertor (ED) or the pump limiters. Measurements of neutral pressures in the ED and outboard pump limiter (OPL) are modeled with 1D parallel transport equations (continuity and momentum balance) for the SOL plasma coupled to 2D neutral particle transport simulations. SOL density and temperature profiles from reciprocating Langmuir probe measurements for a range of volume-averaged densities are renormalized, where necessary, to agree with Langmuir probe measurements in the OPL throat and constitute the upstream boundary conditions for the 1D calculations. Good agreement with measured pressures and exhaust rates are obtained for both the ED and OPL in scans that span a factor of 2-3 in volume-averaged density. The importance of a self-consistent treatment of the plasma and neutral particle transport in the neighborhood of the neutralizer plate is demonstrated, particularly in the stronger recycling regimes characteristic of densities at the high end of the scans. Plasma flow reversal near the plasma/plenum interface is predicted to occur at the higher densities due to the large local ionization source. Predictions of pressure buildup in the plenum behind the prototype vented neutralizer plate agree with experiment if it is assumed that both the tops and partially the sides of the needles comprising the plate are wetted by the plasma. A discharge in which the ED pumps are active is analyzed; the calculated pressure and exhaust rate agree with experiment. The core fueling rate is the same as without pumping, suggesting, as is seen in the experiment, a small density decay rate and significant wall particle depletion.

Keywords: Tore Supra; Ergodic divertor; Neutral confinement and transport; Monte Carlo simulation; 3D model

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1. Introduction

Active density control and heat removal with the ergodic divertor and pump limiters has been demonstrated on the Tore Supra tokamak for a broad range of operating conditions [1]. The ergodic divertor (ED) system [2] consists of six modules located on the low-field side of the torus at $R = 2.38$ m, $a = 0.8$ m. The components of each module include an octopolar coil, five neutralizer plates having poloidal widths of 0.07-0.10 m and particle collection plena connecting the ED throats to titanium getter pumps. The total maximum deuterium pumping speed for six modules is 25 m^3/s. Typical operating currents for the ED octopolar coils are 27 kA and 46 kA. The pump limiter system in Tore Supra is comprised of six vertical modules located at the bottom of the torus and a single outboard pump limiter (OPL) equipped with titanium pumps capable of pumping speeds up to 100 m^3/s. The OPL throat has a radial width of 0.025 m, a poloidal width of 0.5 m and is radially located 0.035 m from the last closed flux surface (LCFS) when the plasma leans on the OPL.

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Results of experiments in which the ED and pump limiter systems were used separately and together for particle exhaust and heat flux control were presented at the 1994 PSI Conference [1]. There it was shown that unpumped deuterium pressures in the plena with the plasma leaning on the ED equaled or exceeded those obtained with the plasma on the OPL in Ohmic discharges (see Fig. 1 of Ref. [1]). For discharges with active pumping, exhaust efficiencies of 3–4.2% were obtained with the plasma on the ED alone and 6% with pumps in both the ED and vertical pump limiters activated. The core density decay rates after termination of gas puffing increase with ED coil current, but correspond at 27 kA to less than 25% of the observed particle exhaust rate. This result and the required gas puff rates earlier in the discharges suggest significant depletion of the wall particle content.

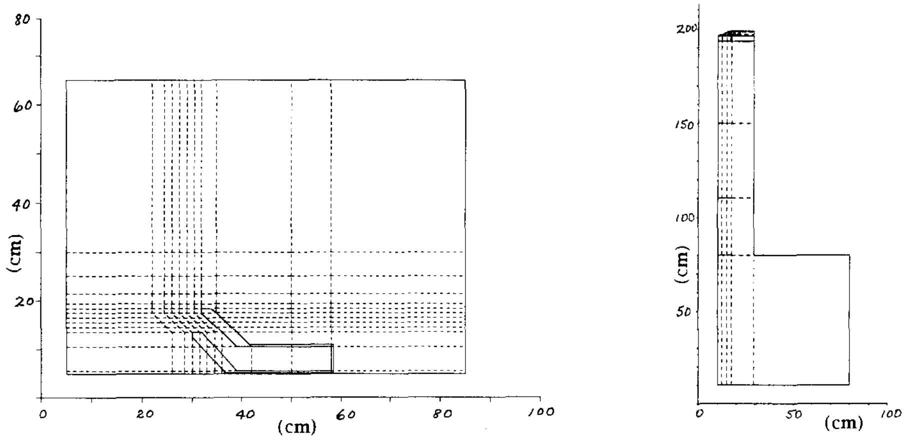
The primary objectives of the work presented here are to analyze the unpumped density scans of plenum pressure in the ED and OPL presented in Fig. 1 of Ref. [1], the pumped discharge depicted in Fig. 3 of Ref. [1] in which the plasma leans on the ED and plenum pressure data obtained with the prototype ED vented neutralizer plate. The analysis of plenum pressure buildup and/or particle exhaust in limiter or divertor discharges requires specification of the geometry of the system (grid, device walls, pumps, etc.), plasma conditions in the region (throat, baffle entrance) of the plasma neutralizing surfaces and models for the neutral particle transport and interaction with the plasma and with the walls of the system. The DEGAS neutral transport code [3] contains the elements specified in the latter requirement.

In Section 2 the model used in the analyses, the upstream boundary conditions of the model and device geometries are discussed. In Section 3 results for the unpumped density scan simulations are discussed and Section 4 describes calculations for the pumped ED discharge and for the vented neutralizer plate. Concluding remarks are given in Section 5.

2. Plasma / neutral transport model

Neutral transport simulations presented here are performed in 2D with plenum dimensions adjusted to give the correct conductance in the flow direction. DEGAS grids for ED and OPL neutral transport simulations are shown in Fig. 1. The grid lines are dashed and the device walls are specified by solid lines. The OPL throat is spanned by three radial grid zones and four zones in the torroidal direction. Langmuir probes that measure electron density and temperature and ion flux are located in the throat approximately 0.04 m radially from the LCFS. The three narrow toroidal zones are each 0.025 m wide and span the assumed 0.075 m distance from the probes to the plate. The domain of the 1D plasma model described below is specified for the OPL by the 3 × 3 array of zones (0.025 m radially by 0.075 m toroidally) extending from the probes to the plate.

In the ED grid shown in Fig. 1 the plasma is assumed to flow from left to right and to wet 0.05 m (radially) of the neutralizer. Five radial zones of equal width span the wetted area of the plate. Upstream boundary conditions for the 1D model are applied at points 0.1 m from the plate. Where applicable, pumping is simulated with a sticking coefficient on the back surface of the plenum. The LCFS is assumed to be at the tip of the neutralizer and the grid is extended radially inward in order to determine the core fueling rates from recycling at the ED plates.



Ergodic Divertor

Outboard Pump Limiter

Fig. 1. 2D geometries for DEGAS calculations of neutral particle transport in the Tore Supra ergodic divertor (ED) and outboard pump limiter (OPL). In the ED (OPL) the throat region is spanned by five (three) radial zones, in each of which the electron and d^+ densities are computed with a 1D plasma model using particle sources from DEGAS.

In both the OPL and ED geometries the fraction of neutral particles that enter the plenum (and contribute to the pressure) after recycling at the plate is a sensitive function of the plasma conditions between the plate and plenum entrance. It was determined from DEGAS calculations for the OPL unpumped density scan that the use of electron densities (constant on field lines) and plate particle fluxes determined from the throat Langmuir probe data did not reproduce the measured plenum pressures at high density. (The fits at lower densities, $\langle n_e \rangle$ less than or about 3×10^{19} m^{-3}, were acceptable.) At higher throat densities, where the mean free path for ionization of neutrals is comparable to the radial width of the throat, it becomes important to incorporate the presheath density drop near the plate. A simple model that adequately describes the plasma in this important region and obviates the need for flux amplification is a goal for this work.

The 1D model for the presheath region is based on the solution of simplified continuity and momentum balance equations. Viscosity and momentum sources from charge exchange, etc. are neglected in the momentum balance equation. In the continuity equation radial diffusion is neglected and particle sources are computed with the DEGAS code. Temperature is assumed to be constant along field lines (justification for this assumption is discussed in Section 3). Mach flow ($M = 1$) is imposed at the neutralizer plate sheath boundary and subsonic flow is imposed elsewhere. If viscosity is neglected, then both the continuity and parallel momentum equations are of first order, requiring one boundary condition for each. Here these are taken to be $M = 1$ at the sheath entrance and the measured value of the electron density from the Langmuir probe at the upstream boundary.

Define a scaled arc length variable $s = (L - L_p)/(L_n - L_p)$, where L is arc length along a field line, L_p is the Langmuir probe location and L_n is the position of neutralizer plate. Note that $s = 0$ corresponds to the probe or upstream boundary (not to the flow stagnation point) and $s = 1$ to the sheath boundary at the plate. Integration of the momentum equation gives the standard expression for density variation in the presheath:

$$n(s) = n(0)\{1 + M^2(0)\}/\{1 + M^2(s)\}. \tag{1}$$

With S the particle source from DEGAS, the continuity equation can be integrated to give

$$n(s)M(s) = n(0)M(0) + (L_n - L_p)\int_0^s S(s')\mathrm{d}s'/C_S(0), \tag{2}$$

where $C_S(0)$ is the ion sound speed (assumed independent of s). Combining Eqs. (1) and (2) evaluated at the sheath entrance yields a quadratic equation for the Mach number at the upstream boundary. The solution is:

$$M(0) = 1 - \left\{(L_n - L_p)\int_0^1 S(s)\,\mathrm{d}s \Big/ \tfrac{1}{2}n(0)c_s(0)\right\}^{1/2}, \tag{3}$$

where the negative sign of the radical has been chosen for subsonic flow. Note that $M(0)$ can be negative if the integrated ion source exceeds the parallel ion flux at the upstream boundary (Langmuir probe particle flux). Define:

$$\beta = \left[1 + M^2(0)\right] \Big/ \Big\{2M(0) + (L_n - L_p)\int_0^s S(s')\,\mathrm{d}s' \Big/ \left[n(0)C_S(0)/2\right]\Big\} \tag{4}$$

and $M(s)$ is similarly given by the solution of a quadratic equation

$$M(s) = \beta \pm \left[\beta^2 - 1\right]^{1/2} \tag{5}$$

where the plus (minus) sign is used for reversed (normal) flow. The parallel ion flux at the plate is given by:

$$\Gamma(1) = n(0)C_S(0)M(0) + (L_n - L_p)\int_0^1 S(s)\,\mathrm{d}s. \tag{6}$$

The 1D plasma model outlined above is coupled to the DEGAS neutral transport code and run iteratively to convergence. Typically five to ten iterations are required, with more iterations the larger the volume-averaged density. The number of neutral particle flights in DEGAS is chosen to give a standard deviation in the plenum pressure of 5–10%.

3. OPL and ED unpumped density scan simulations

A density scan of plenum pressure and throat electron density and temperature, with the plasma leaning on the OPL [4,5], spans the volume-averaged density range 1.5×10^{19}–5×10^{19} m^{-3}. SOL profiles of density and temperature are also available from the reciprocating Langmuir probe (RLP), located near the top of the torus, permitting a comparison of plasma parameters at the radial location of the OPL throat Langmuir probe (TLP) with those measured approximately 80° poloidally upstream from the TLP. This comparison for several values of $\langle n_e \rangle$ showed no significant variation of the electron temperature along magnetic field lines connecting the two probes. In Fig. 2 the ratio $n_e(\mathrm{TLP})/n_e(\mathrm{RLP})$ is shown as a function of $\langle n_e \rangle$ and indicates that the OPL throat density exceeds that at the RLP for $\langle n_e \rangle$ greater than about 4×10^{19} m^{-3}. It is not clear whether pressure balance along field lines is affected by momentum sources in the throat at high densities (since no significant T_e drop is seen). In the calculations presented here we assume a 'recycling halo' surrounding the OPL that gives rise to larger densities in the SOL for $\langle n_e \rangle > 3.5 \times 10^{19}$ m^{-3}. Consequently, the RLP density profiles are renormalized by the ratio depicted in Fig. 2 when used as upstream boundary conditions in the 1D model.

Since the RLP temperature profiles are almost linear in minor radius and do not show a strong variation in decay

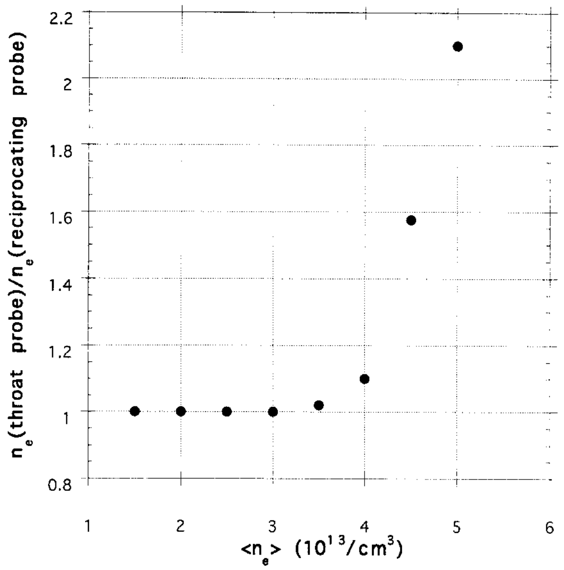


Fig. 2. The ratio of electron density measured by the OPL throat Langmuir probes to that measured at the same minor radius by the reciprocating Langmuir probe (RLP) is shown as a function of volume-averaged density. The corresponding RLP radial profiles, normalized by this ratio, are used as upstream boundary conditions for the 1D calculations of plasma density.

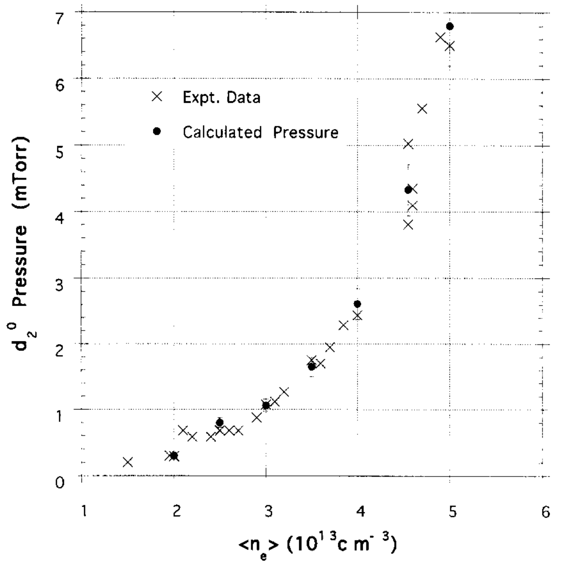


Fig. 3. The unpumped deuterium pressure in the OPL plenum is calculated with the DEGAS code using measured electron temperatures and densities from 1D model calculations in the throat region. The error bars on the calculated pressures represent one standard deviation, as determined by DEGAS. The ion flux at the neutralizer plate is determined from the 1D model assuming an edge Z_{eff} that is 25% larger than the corresponding measured core value.

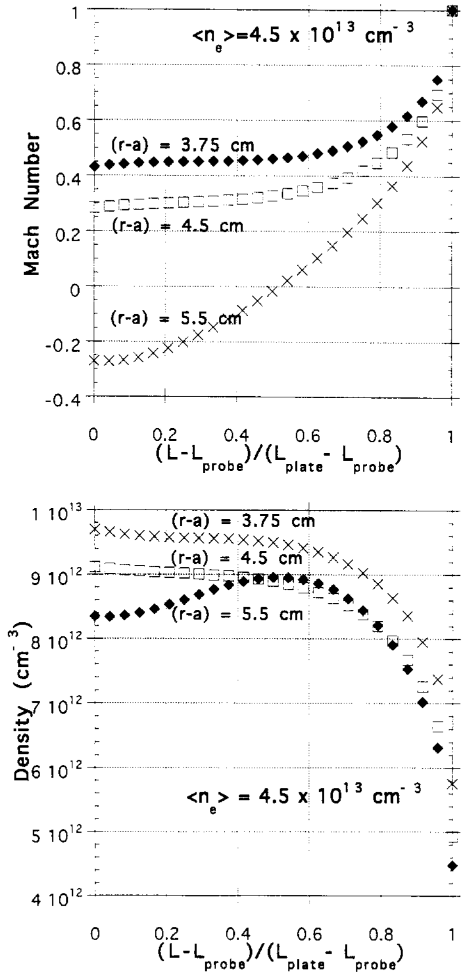


Fig. 4. d$^+$ densities and flow Mach numbers at three radii in the OPL throat are shown as functions of the normalized distance from the throat Langmuir probe location. With the assumption of constant temperature along field lines, the strong d$^+$ source region at the plasma-plenum interface results in a region of reversed flow in the model calculations.

length as a function of $\langle n_e \rangle$, we have approximated both the density and temperature profiles as linear functions of radius with decay lengths λ_n and λ_T, respectively. For the OPL simulations we take $\lambda_n = 0.163$ m and $\lambda_T = 0.12$ m. Due to the unavailability of RLP data corresponding to the ED density scan and the complications associated with mapping through the ergodic layer each point on the moving RLP to the corresponding point on the ED neutralizer plate, we have chosen to modify the OPL profiles for use in the ED density scan analyses. The plasma minor radii are typically larger and the SOL electron temperatures are smaller for the ED discharges. Consequently, the radial decay lengths for both density and temperature are reduced to 0.08 m and the temperatures $T_e(r = a)$ are reduced by 50% from those used in the OPL scan. $\langle n_e$ at

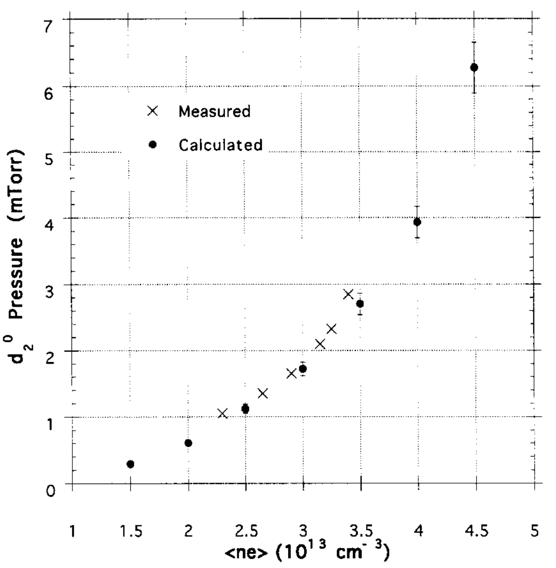


Fig. 5. The unpumped deuterium pressure in a plenum of the ED is calculated with the coupled DEGAS code and 1D plasma model using plasma parameter profiles based upon the OPL density scan but modified to reflect changes in the SOL seen with ED operation.

the LCFS is not changed from that used in the OPL calculations.)

As shown in Figs. 3 and 5, measured unpumped plenum pressures are well reproduced by the model calculations for both the OPL and the ED density scans. This agreement is obtained without the imposition of flux amplification between the upstream boundary of the 1D model and the neutralizer plates. (The plate particle flux given by Eq. (6) is sufficient over the entire range of $\langle n_e \rangle$.) In Fig. 4 the calculated d^+ densities and flow Mach numbers at three radii in the OPL throat are shown for $\langle n_e \rangle 4.5 \times 10^{19}$ m^{-3}. The strong d^+ source rate at the plasma/plenum interface results in a region of reversed flow and a corresponding peaking of the density midway between the TLP and the neutralizer plate.

4. Ergodic divertor pumping and prototype vented plate simulations

Initial exhaust studies with the Tore Supra OPL [6] demonstrated strong particle exhaust but only weak effects on the core density. Those and later studies [7] suggested that wall outgassing mediated by a strongly ionizing SOL explained the apparent decoupling of the core and particle exhaust. Similar behavior is seen with the plasma leaning on the ergodic divertor in the data presented in Fig. 3 of Ref. [1]. It should be emphasized that density control is still possible in these discharges even though pumping results in small density decay rates, i.e., the walls continue to pump when the Ti getters are active and the density is controlled via the gas puff rate.

The ED Ohmic discharge referred to above is analyzed at $t = 8$ s, which is just after the termination of the gas puff. The ED coil current is 27 kA, the plasma minor radius is 0.75 m, the volume-averaged density is 3.5×10^{19} m^{-3} and the pumping speed (all six modules) is 11 m^3/s. The observed density decay rate is less than 25% of the particle exhaust rate. In the simulation a sticking coefficient at the back surface of the plenum is adjusted to give a pumping speed of 9.5 m^3/s (less than the measured value due to conductance limitations). At points 0.1 m upstream from the neutralizer plate, the plasma profiles are assumed to be the same as those used in the corresponding unpumped case. The 1D plasma model and DEGAS are iterated with the assumption that upstream boundary conditions are unchanged by active pumping.

Results of the model calculations agree well with the experimental observations. The plenum pressure is reduced from 2.7 mTorr (no pumping) to 1. 16 mTorr (with pumping). The projected particle exhaust rate for all six modules is 10.8 Torr l/s, corresponding to 7% of the integrated neutralizer plate particle flux. The calculated core fueling rate from divertor recycling is the same as that calculated for the unpumped case, indicating, as seen in the experiment, a small core density decay rate. Only small changes are seen in the computed density profiles. The results of this simulation strengthen the conclusion (based on the measurements) that most of the exhaust flux at $t = 8$ s corresponds to wall depletion.

Enhanced power handling capability with the ED system is afforded by the introduction of vented neutralizer plates. The particle collection and exhaust characteristics [8] of this system have been tested with the reconfiguration of one of the bottom vertical limiters and with a prototype vented plate in one of the ED modules. The prototype ED plate is instrumented with a Langmuir probe and a baratron to measure plenum pressure behind the vented neutralizer. Two unpumped discharges are examined and calculations of plenum pressure, using particle fluxes from the Langmuir probe, are compared to measurements. In both shots the ED coil current is 46 kA and the volume-averaged density is 3×10^{19} m^{-3}. Shot 19825 has 3 MW of ICH and shot 19808 is Ohmic only. Plasma parameters at the vented plate are $T_e = 44$ eV, $n_e = 1.17 \times 10^{19}$ m^{-3} for 19825 and $T_e = 20$ eV, n_e 3.2×10^{18} m^{-3} for 19808. The measured plenum pressures are 0.3–0.45 mTorr (0.11–0.18 mTorr) for 19825 (19808). The calculated plenum pressure for shot 19825 (19808) is 0.43 mTorr (0.12 mTorr).

Neutral transport calculations of plenum pressures were performed for ranges of plasma parameters to test the sensitivity of vented-plate particle collection to plasma conditions at and near the plate. The neutral particle flux into the plenum is found to be relatively insensitive to the plasma temperature at the plate (the $T^{1/2}$ dependence of the plate ion flux is partially balanced by corresponding changes in throat plasma opacity) and to vary roughly as the 2/3 power of the density. The best fits to the pressure data are obtained when the ion flux to the neutralizer plate is assumed to wet both the tops and partially the sides of the needles comprising the plate. Based upon the shape and orientation of the needles with respect to the magnetic field, this assumption is justified.

5. Summary and conclusions

The importance of a self-consistent treatment of the plasma and neutral particle transport in the neighborhood of the neutralizer plates of the Tore Supra OPL and ED is demonstrated with a simple 1D model for plasma in the throat regions coupled to 2D DEGAS neutrals calculations. In particular, the resulting density variation along field lines and attendant effects on the throat plasma opacity, are essential to fitting plenum pressure data for $\langle n_e \rangle$ greater than about 3×10^{19} m^{-3}. The necessity of invoking flux amplification to account for recycling in the near-plate plasma is thus avoided.

In both the OPL and ED the strong ionization source at the plasma/plenum interface leads to a region of reversed flow in the model calculations at higher densities. ED pumping and core fueling calculations suggest, as seen in the experiment, a small core density decay rate and significant wall depletion. Neutral transport calculations of pressure buildup in the plenum behind the ED prototype vented neutralizer plate reproduce the baratron measurements if it assumed that plasma wets both the tops and partially the sides of the needles that comprise the plate.

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