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Particle exhaust modeling for the collaborative DIII-D advanced divertor program *

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A principal objective of the collaborative DIII-D Advanced Divertor Program (ADP) is to achieve density control in H-mode discharges with edge biasing and with continuous particle exhaust at a rate determined by the external fueling sources (typically 20 Torr · L/s). The divertor baffle–bias ring system has been optimized for pumping speeds ≈ 50000 L/s with the neutrals transport code DEGAS. With an entrance slot conductance of 50000 L/s, a pumping speed of the same order is required to remove half of the ≈ 40 Torr · L/s that enters the baffle chamber for typical H-mode discharges. Increasing the exhaust fraction with higher pumping speed is self-limiting, owing to the attendant reduction of the recycling flux. The effects of pumping on the plasma core, scrape-off layer (SOL), and divertor have been estimated with a model that self-consistently couples the transport in these regions. The required ≈ 50000 L/s pumping speed can be achieved with either titanium getter pumps or cryopumps. Evaluation of both systems has led to the conclusion that cryopumps will be more compatible with the environment of the DIII-D divertor.

1. Introduction

As the duration of tokamak discharges increases to pulse lengths of many seconds (≤ 30), wall recycling of plasma particles approaches unity; that is, wall pumping becomes negligible. As a consequence, external particle sources must be balanced by continuous exhaust with a pump limiter or a pumped divertor. However, pumping might interfere with the need for maximum recycling in divertors of future devices such as the International Thermonuclear Experimental Reactor (ITER). The concept of high recycling at the divertor plate, entailing high densities and low electron temperatures, is presently the only scenario conceivable for protecting the divertor plate from high sputter erosion. Since the flux multiplication at the plate is likely to decrease with increased pumping, it will be crucial to find a balance between necessary particle exhaust and adequate recycling rates at the plate.

The characteristics of a pumped divertor will be studied as part of the collaborative Advanced Divertor Program (ADP) in the DIII-D tokamak. A possible immediate benefit for DIII-D operation is that divertor pumping may allow density control independent of the plasma current. In present H-mode discharges, the density increases with plasma current so that independent current and density scans cannot be performed [1].

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2. Exhaust requirements and baffle configuration

In discharges with neutral beam injection, the minimum exhaust rate is determined by beam fueling, which corresponds to ≈ 20 Torr · L/s for 10 MW of power injected into DIII-D. If other external sources (e.g., pellet injection) are present, the exhaust rate must be correspondingly higher. However, if the recycling coefficient can be kept low by means of wall conditioning, the wall will pump some of the recycling flux, and the external fueling rate will be balanced by the combined wall pumping and divertor pumping. With a low recycling coefficient, the amount of wall pumping can considerably exceed the exhaust rate of the divertor, as demonstrated below.

The divertor baffle in DIII-D was designed for both bias experiments and pumping experiments [1]. Here we address divertor pumping only. Fig. 1 shows the baffle configuration and a schematic view of the scrape-off layer (SOL) plasma in contact with the vessel floor at the inner and outer divertor strike points. The water-

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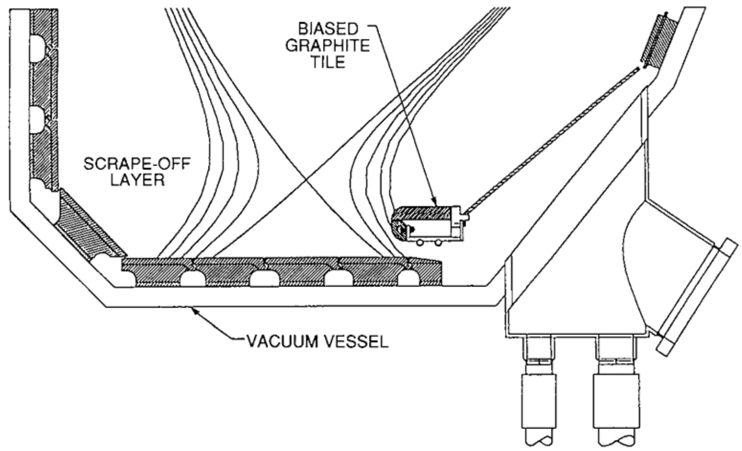

Fig. 1. Schematic view of divertor baffle and scrape-off layer near the strike points.

cooled bias ring and attached baffle plates were designed for minimum impact on the normal DIII-D experimental program, with particular emphasis on the restriction not to interfere with full-size limiter-plasma operation. The divertor throat has a conductivity of 50000 L/s for thermal deuterium gas. Plans are to install a pump with a pumping speed at least as high as the throat conductance. As shown in section 3, less than 10% of the total recycling flux enters the divertor chamber, but this appears to be sufficient for the required exhaust rates.

3. Particle exhaust optimization

Within constraints imposed by other aspects of the DIII-D experimental program, the baffle–bias ring configuration is optimized for maximum particle exhaust at a given pumping speed [2]. The main issues in the optimization study are neutral particle mean free path near the strike point, solid angle for the collection of neutrals, backflow impedance for neutral gas in the baffle chamber, ionization and subsequent recycling of neutrals, reduction of core plasma fueling rates, and conductance limitations imposed by elements of the radiation shield (for cryopumps).

Magnetic flux surfaces and plasma parameters from the H-mode documentation series are used in the neutral transport code DEGAS [3] to establish the dependence of baffle entrance slot conductance, baffle pressure, and particle throughput on the geometry of the entrance slot. Although the plasma density, temperature, and total recycling flux near the outer strike point are expected to change with active pumping, these quantities are assumed to be constant in these calculations. Fig. 2 displays the total particle flux $\Gamma(h)$ entering the baffle chamber, the corresponding D_2^0 pressure $p(h)$ inside the baffle chamber, and the entrance slot conductance $C(h)=\Gamma/p$, for typical quiescent H-mode conditions. The conductance is calculated with the average pressure in the baffle. As such, it represents the total conductance from the pump region behind the bias ring (see fig. 1) to the plasma. The conductance of the entrance slot alone is therefore slightly larger than that shown in fig. 2.

For a given pumping speed S, the particle throughput $T=\Gamma S/(S+C)$ is maximized with respect to the slot height h by solving $\mathrm{d}T/\mathrm{d}h=0$. Our studies have shown that titanium pumps or cryopumps capable of 50000 L/s can be accommodated within the space limitations of the baffle chamber. The optimum slot height for this pumping speed is $h \approx 3$ cm, and the corresponding entrance slot conductance is 50000 L/s. A configuration featuring a conceptual cryopump design that is optimized for $S=50000$ L/s is shown in fig. 3.

4. Global particle balance as a function of pumping speed and recycling

The recycling particle flux is a sensitive function of the recycling coefficient, and the effective recycling coefficient is reduced by divertor pumping. Hence, the total recycling flux becomes a sensitive function of the pumping speed. Since the exhaust flux is proportional

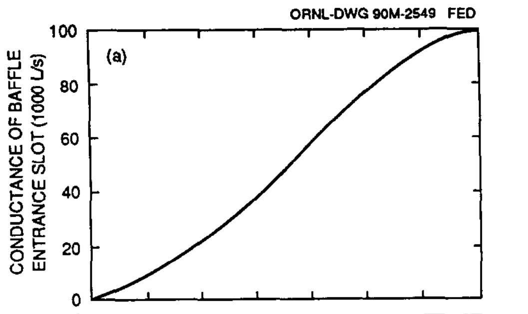

Fig. 2. (a) Conductance of baffle entrance slot, (b) average D_2^0 pressure in baffle, and (c) total number of particles entering baffle as functions of baffle entrance slot height.

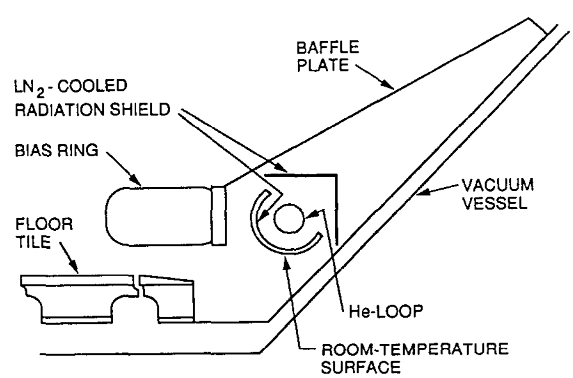

Fig. 3. Configuration of the baffle, bias ring, and cryopump system optimized for $S = 50000$ L/s. Approximately 50% of the neutral flux into the baffle is pumped.

to the recycling flux, it follows that the exhaust is self-limiting with pumping speed. To study the correlation between exhaust and pumping speed, we couple the particle balance equations of plasma core, edge plasma, pumped divertor, and wall:

$$\mathrm{d}N_C/dt = \Gamma_F - (N_C/\tau_p)(1 - R_G), \quad (1)$$

$$\mathrm{d}N_S/\mathrm{d}t = (N_C/\tau_p)(1 - R_G) - (N_S/\tau_p') \times \{1 - [R_L - f(S/S + C)]\}, \quad (2)$$

$$\mathrm{d}p/\mathrm{d}t = [(fN_S/\tau_p')/V] - [(S + C)/V]p, \quad (3)$$

$$\mathrm{d}N_W/\mathrm{d}t = (N_S/\tau_p')(1 - R_L) - \Gamma_W. \quad (4)$$

Eq. (1) described the particle balance in the plasma core: N_C is the total number of core plasma particles, Γ_F the external fueling rate, τ_p the global particle confinement time in the core, and R_G the global recycling coefficient corresponding to the core fueling. Eq. (2) represents the particle balance in the SOL: N_S is the number of particles, τ_p' the particle confinement time in the SOL, f the fraction of the recycling flux that enters the divertor throat, S the divertor pumping speed, and C the divertor throat conductance. Eq. (3) describes the particle balance in the divertor chamber, with V the volume and p the neutral pressure, and eq. (4) describes the particle balance in the wall surface, with N_W the particle inventory in the wall surface and Γ_W the particle flux diffusing into the bulk of the wall.

By setting all time derivatives equal to zero, we can deduce expressions for the steady-state particle fluxes: the total recycling flux $N_S/\tau_p' = \Gamma_R = \Gamma_F/\{1 - [R_L - fS/(S + C)]\}$, the divertor exhaust flux $\Gamma_E = \Gamma_R fS/(S + C) = pS$, the wall pumping rate $\Gamma_W = (1 - R_L)\Gamma_R$, and the steady-state divertor pressure $p = f\Gamma_R/(S + C)$. Typical values of $f = 0.08$ and $C = 50000$ L/s were determined with DEGAS [3]. Pumping the divertor changes the recycling coefficient R_L to an effective recycling coefficient $R = R_L - fS/(S + C)$, which, in turn, affects all particle fluxes. For a given recycling coefficient, the divertor pumping speed determines the fractions of the particle flux pumped by the divertor and by the wall. For steady-state conditions, the total removed flux must equal the external fueling, $\Gamma_E + \Gamma_W = \Gamma_F$.

The fluxes Γ_E and Γ_W are plotted in fig. 4 for $\Gamma_F = 20$ Torr · L/s with $R_L = 0.90$ and 0.99. If the walls are conditioned for low recycling, $R_L = 0.90$, and the pumping speed is 50 000 L/s, only about 6 Torr · L/s is pumped by the divertor, and the rest is pumped by the wall. If the recycling coefficient increases to, for example, $R_L = 0.99$, wall pumping is low, but the divertor

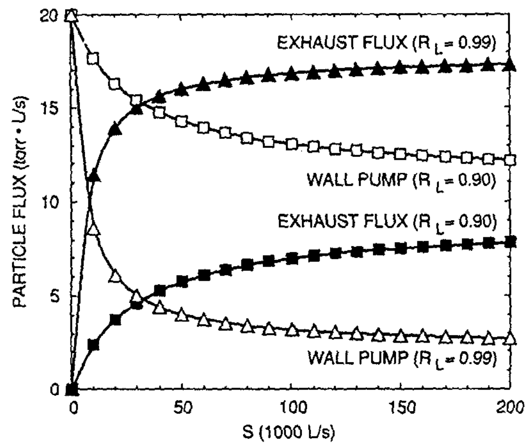

Fig. 4. Divertor exhaust and wall pumping as a function of recycling and pumping speed.

exhaust rate is high as a consequence of the large recycling flux; fig. 4 indicates that the divertor exhaust reaches 16 Torr · L/s; that is, only 4 Torr · L/s is pumped by the wall. The sum of the divertor exhaust and wall pumping is equal to the external fueling rate, which, of course, is determined by the density limit and particle confinement time of the core plasma.

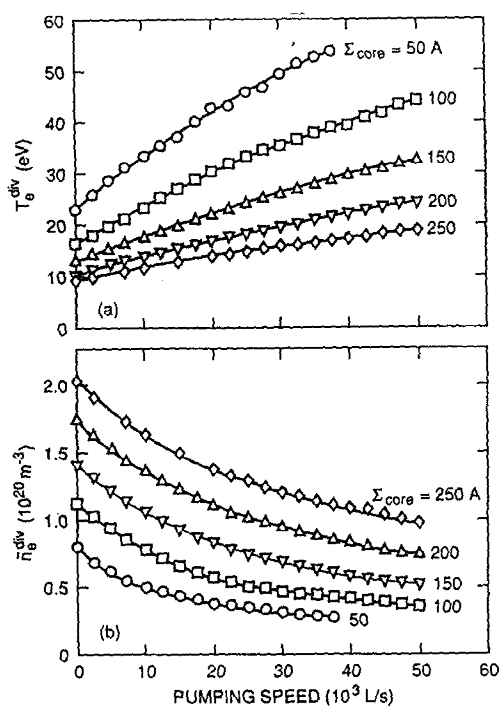

Fig. 5. Variation of (a) the outer divertor plate temperature and (b) the electron density at the outer divertor plate as a function of pumping speed for central fueling rates from 50 to 250 A. Temperatures in the range from 10 to 20 eV are predicted for $\Sigma_{core} \sim 150$–250 A (1 A $= 6.25 \times 10^{18}$ particles/s $= 0.09$ Torr · L/s).

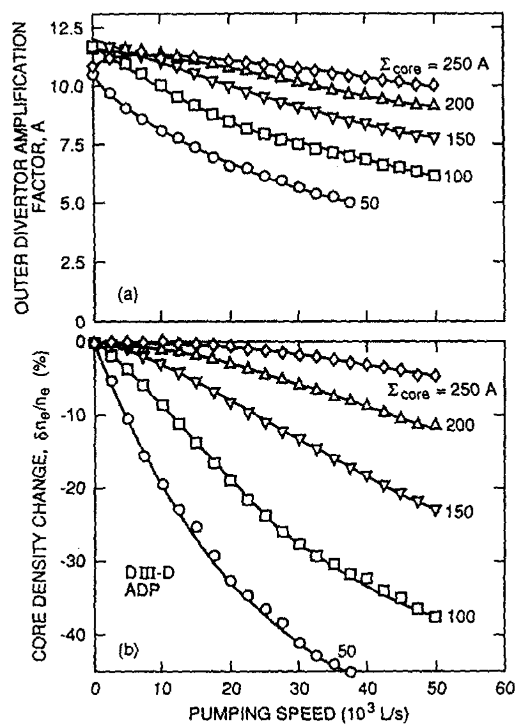

Fig. 6. (a) Outer divertor amplification factor (ratio of divertor particle flux to throat particle flux) $A \sim 9$–12 for $\Sigma_{core} \sim 150$–250 A. (b) Predicted core density change with pumping. Large decreases are predicted with low core fueling rates. The pre-VORTEX model predicts particle confinement times from 150 to 300 ms, with an assumed ELM diffusivity of 10^4 cm^2/s.

5. Effect of pumping on core and divertor plasma

To determine the effect of pumping on plasma performance, an internally consistent model for particle transport in an open divertor geometry has been developed. Embodied in a new code, pre-VORTEX, the model couples the particle balance in the plasma core, the SOL, the open divertor channels, and the vacuum regions. The plasma core is taken to have a relatively quiescent center and a less well confined outer region characterized by an edge-localized mode (ELM) frequency and amplitude. The radial (1-D) density conservation equation is solved, assuming that all external ionization occurs in the outer (ELM) region and all external fueling (e.g., from neutral beams) occurs in the central region. The SOL is modeled with 1-D parallel and perpendicular transport, assuming particle influx from the plasma core and ionization of recycling neutrals from the wall and divertors. A two-point divertor channel model integrates the 1 -D parallel transport equations between the throat and the divertor plates. This is similar to previous "simple" models, but new physical processes (hydrogen charge exchange, impurity thermal charge exchange, and flux-limited parallel transport) are considered. The differing recycling properties of the wall regions and divertor plates enter in the neutral particle balance, which couples the nine separate regions of the open divertor pumping geometry. No explicit watershed symmetry condition is imposed for the scrape-off layer solutions, and particle balances for the various regions are coupled. A detailed description is given by Hogan [4].

Given local plasma and SOL diffusivities, wall recycling properties, and magnetic geometry, the model predicts both divertor properties and the volume-averaged density and global particle confinement time. The final model, VORTEX, will be applied to the detailed analysis of divertor confinement experiments; it is coupled to a $1\frac{1}{2}$-D transport code and uses geometric input from a 2-D equilibrium (or from experimental fitting codes), experimentally measured core profiles, and parameters measured in the SOL. The pre-VORTEX model has been compared as a stand-alone code with typical data from the DIII-D experiment and applied to the proposed DIII-D ADP.

The effect of pumping on the particle balance in a discharge with 5 MW of injected power at various fueling ratios has been examined for the nominal parameters of DIII-D and the pump geometry described in section 6. Fig. 5 shows the predicted variation of the outer divertor electron temperature and density with pumping speed for central fueling rates from 50 to 250 A (or from 3.1×10^{20} to 1.6×10^{21} particles per second). High recycling conditions are predicted, even for relatively low core fueling rates, with T_e in the range 10–20 eV. Fig. 6 shows the corresponding outer divertor amplification factor, which decreases from 12 to 5 without fueling and is ≈ 10 with 200 to 250A of central fueling. The drop in core plasma density is large without core fueling ($\sim 50\%$).

6. Pumping system

The required pumping speed of 50000 L/s can only be achieved with in-vessel pumping. With appendage pumps, the pumping speed would be limited to < 15000 L/s by the toroidal conductance of the baffle chamber and the number and size of the available ports. Two different pumping schemes have been investigated: titanium (Ti) getter pumps and cryopumps.

The getter pump, based on the design of Sledziewski and Druaux [5], comprises an array of annular disks on which a thick layer (~ 1 μm) of Ti is deposited by an axial filament. In our own experiments with thick Ti Films [6], (1) the pumping speed is not constant but decreases from > 10 L/s $\cdot$ cm^2, at fluences corresponding to less than a monolayer, to 0.5 L/s $\cdot$ cm^2 as the cumulative gas loading reaches about 0.015 Torr $\cdot$ L/cm^2; (2) the pumping surface is poisoned by gases such as O_2 and CO_2; and (3) rejuvenation of the surface by baking at 380°C for 4 h and depositing a thin (0.1 μm) layer of Ti, as prescribed in ref. [5], did not help to recover the pumping capacity. These results, in conjunction with the lack of access to the pumps after they are installed, suggested that Ti getter pumps are not appropriate for this application.

Cryocondensation pumping is well established and has found wide applications. However, inside the tokamak this technique is complicated by (1) radiation from high-temperature surfaces, (2) electromagnetic effects that can contribute significant heat loads, (3) plasma disruption forces, (4) energetic particle fluxes from the diverted plasma, (5) restrictions on materials compatible with tokamak operation, (6) compatibility with glow-discharge wall conditioning, and (7) severe access restrictions.

The cryocondensation pump that is being developed for DIII-D is schematically shown in fig. 3. A helium-cooled tube forms the cryocondensation surface and is surrounded by a nitrogen-cooled radiation shield. A room-temperature shield around the liquid-nitrogen-cooled surface faces the particle entrance region to prevent a potential problem of desorption of condensible impurities (e.g., water) by energetic particles or photons. To prevent induction of currents, the pump will be electrically insulated from the vacuum vessel and provided with insulating breaks outside the vessel. Estimates of all major sources of heat loading have been made in a coaxial geometry [7], and the design was found to be dictated by the need to accommodate the helium glow-discharge conditioning in DIII-D, performed before each shot. Currently, the chamber pressure is raised to about 60 mTorr of helium for a few seconds before the glow strikes. Accommodating the high heat load during this period may require allowing the pump to regenerate, in addition to using the latent heat of vaporization of liquid helium. Electron-assisted glow, with maximum helium pressures in the 1 to 2 mTorr range, is being investigated in DIII-D [8]. If this is successful, regeneration of the cryopump between tokamak discharges may not be necessary.

7. Summary and conclusions

The particle exhaust rate for the DIII-D advanced divertor was maximized subject to the constraint of minimal interference of the baffle–bias ring system with other aspects of the experimental program. Consequently, the particle exhaust rate was optimized to conform to this restriction. Computer simulations (DEGAS) show that < 10% of the recycling flux enters the divertor baffle. Nevertheless, the achievable exhaust rate appears to be acceptable. The recycling particle flux is a very sensitive function of the recycling coefficient. Divertor pumping has a strong impact on this delicate balance because it changes the effective recycling coefficient. It is difficult to predict the effect of divertor pumping on the core plasma parameters. A new code, VORTEX, that couples all relevant regions of plasma core and edge has been developed to study the global effects of divertor pumping. Divertor pumping experiments in DIII-D will provide an excellent opportunity to validate this and other codes needed to predict the divertor performance of future devices such as ITER. Titanium getter pumps and cryopumps were evaluated. Cryopumps appear more suitable for this application. Design and operation of a continuous pumping system inside a tokamak is a prerequisite for steady-state machines, and the DIII-D experiments will provide a valuable data base for future devices.

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