[5]T. K. Chu, H. P. Furth, J. L. Johnson, C. Ludescher, and K. E. Weimer, private communications, and Princeton Plasma Physics Laboratory Report No. PPPL-1796, 1981 (unpublished).
[6]A. H. Boozer and G. Kuo-Petravic, Phys. Fluids 24, 851 (1981).
[7]R. E. Potok, P. A. Politzer, and L. M. Lidsky, Phys. Rev. Lett. 45, 1328 (1980).
[8]L. S. Hall and B. McNamara, Phys. Fluids 18, 552 (1975).
[9]M.N. Rosenbluth, R. D. Hazeltine, and F. L. Hinton, Phys. Fluids 15, 116 (1972).

# Cool, High-Density Regime for Poloidal Divertors

M. Petravic, D. Post, D. Heifetz, and J. Schmidt
*Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544*
(Received 29 June 1981)

Calculations have been performed which demonstrate the possibility of operating poloidal divertors at high densities and low temperatures. Ionization of recycling neutral gas near the divertor neutralizer plate amplifies the input particle flux thereby raising the plasma density and lowering the plasma temperature. Low-temperature, high-density operation should reduce the erosion rate of the divertor walls and plate, and ease the pumping requirements in future large tokamaks.

PACS numbers: 52.55.Gb

Early design work for proposed very large reactor-sized tokamak experiments, such as INTOR[1] and ETF,[2] has indicated that one of the chief difficulties of such devices is handling the particle and heat outfluxes of ~$10^{23}$ particles/sec and ~100 MW. Applications of simple edge models[3] have led to the expectation that the edge would have a high temperature (500–2000 eV) and low density ($n_e \sim 10^{11}$–$10^{12}$ particles/cm$^3$). For such conditions, the average energy per particle would be in the kiloelectronvolt range, resulting in erosion rates due to sputtering on the order of 25 cm/yr for materials such as iron.[4]

We have constructed a two-dimensional model for the steady-state plasma and neutral-gas flow in a poloidal divertor. The calculation is done in a Cartesian geometry with a rectangular divertor (Fig. 1) with plasma flowing into the divertor and striking the neutralizer plate near a pumping duct. We have used a set of flux-conserving fluid equations (1)–(4) to describe the plasma. Electron inertia was neglected and charge neutrality used to eliminate the electric field from (3) and (4):

$$\frac{\partial(nv_\xi)}{\partial\xi} = S_n(\xi, y) + \frac{\partial}{\partial y}\left(D\frac{\partial n}{\partial y}\right), \tag{1}$$

$$\frac{\partial}{\partial\xi}\left[n(mv_\xi^2 + T_i + T_e)\right] = S_p(\xi, y) + \frac{\partial}{\partial y}\left(mv_\xi D\frac{\partial n}{\partial y}\right), \tag{2}$$

$$\frac{\partial}{\partial\xi}\left[nv_\xi(\tfrac{5}{2}T_i + \tfrac{1}{2}mv_\xi^2)\right] = -v_\xi T_e\frac{\partial n}{\partial\xi} + S_{E_i}(\xi, y) + \frac{\partial}{\partial y}\left(\left[\tfrac{5}{2}T_i + \tfrac{1}{2}mv_\xi^2\right]D\frac{\partial n}{\partial y}\right), \tag{3}$$

$$\frac{\partial Q_e}{\partial\xi} = v_\xi T_e\frac{\partial n}{\partial\xi} + S_{E_e}(\xi, y) + \frac{\partial}{\partial y}\left((\tfrac{3}{2}T_e)D\frac{\partial n}{\partial y}\right). \tag{4}$$

$S_n$, $S_p$, $S_{E_i}$, and $S_{E_e}$ are the particle, momentum, and ion and electron energy source terms due to ionization, charge exchange, and radiation of the recycling neutral atoms. $\xi$ is the coordinate along the field line, $y$ is the coordinate perpendicular to the flux surface, and $D$ is the cross-field diffusion coefficient.

The first three boundary conditions are the particle flux $\Gamma$ and the electron and ion energy fluxes, $Q_e{}^0$, $Q_i{}^0$, at the divertor throat. The other two boundary conditions are the electron energy flux at the sheath boundary at the neutralizer plate, $Q_e{}^{\rm sh} = \gamma 2T_e(nv_\xi)^{\rm sh}$, and $v_\xi$, the plasma

 

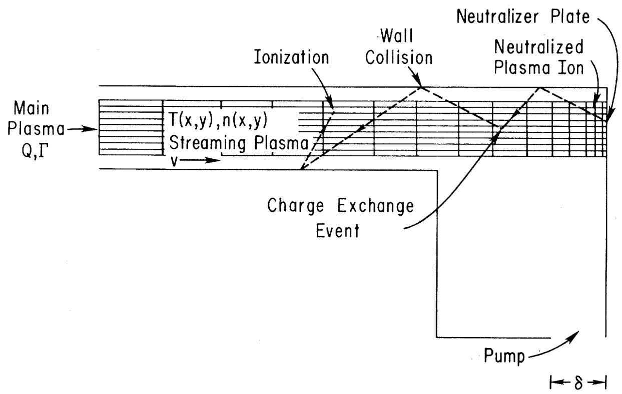


FIG. 1. Model divertor chamber.

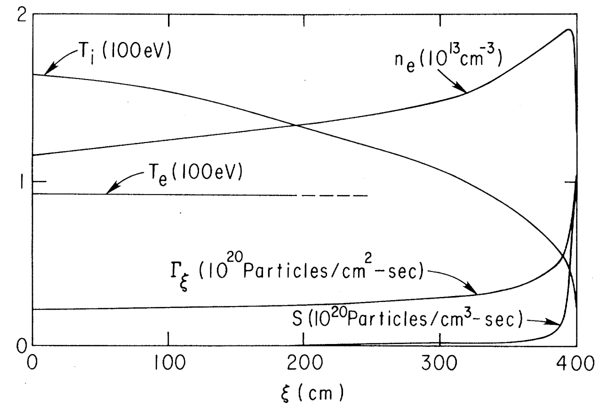


FIG. 2. Calculated plasma parameters along the separatrix in the modified PDX divertor for a pump opening of 4 cm.

flow velocity computed *at the sheath boundary* from $\frac{1}{2}(mv_\xi^2)^{\text{sh}} = \frac{5}{6}T_i^{\text{sh}} + \frac{1}{2}T_e$. (The suffix "sh" indicates the sheath boundary.) The plasma flowing into the sheath flows at the *local* sound speed. $\gamma$ is about 2.9 for the case of no secondary electron emission. $T_e$, assumed constant along field lines, was obtained by integrating (1) and (4), and combining the result with $T_e = Q_e^{\text{sh}}/(2\gamma n v_\xi)^{\text{sh}}$.

The neutral-gas source terms are computed by using Monte Carlo techniques.[4] Neutrals are assumed to be formed when plasma ions accelerated across the sheath strike the neutralizer plate. Incident plasma ions are either reflected as fast neutrals with an energy and angular spectrum chosen to match experimental data, or trapped in the bulk material of the neutralizer plate, where they diffuse to the surface, and desorb as wall-temperature molecules.

The relevant collision processes such as charge exchange and electron impact ionization and dissociation are included for both atomic and molecular hydrogen. In most of the cases of interest, the electron temperature is high enough so that the molecules are ionized, and then dissociated into equal numbers of protons and hydrogen atoms. Neutrals that strike the wall are reflected in a similar fashion to ions striking the neutralizer plate. To make sure that the ions created by ionization or charge exchange within the divertor are not escaping through the throat, they are divided into energy groups and then followed until their velocity satisfies $v_\xi \geq 0$. Thereupon they are included in plasma sources.

Calculations were performed for a variety of divertor geometries. This study was done using parameters roughly corresponding to those expected on PDX,[5] and with the divertor modeled as an axisymmetric rectangular duct with pumping (Fig. 1). The divertor channel is 40 cm long and 6 cm wide with the $x$ coordinate normal to the plate, and the magnetic field forming an angle of 95.74° with the normal. The plasma is 4 cm wide with a 1-cm vacuum gap on each side of the plasma. The pumping chamber is $12 \times 12$ cm$^2$ with an opening at the bottom that was varied from 2 cm wide to 6 cm wide, thus varying the pumping speed at the neutralizer plate from 12 000 to 36 000 l/sec (air at 25°C). The heat flux was 2 MW of which 85% was in the electron channel and 15% in the ion channel. The particle flux was $5.8 \times 10^{18}$/cm sec, corresponding to a total flux of $3.9 \times 10^{21}$/sec, and to a particle confinement time of about 50 msec on PDX. The separatrix was 0.4 cm above the center line of the divertor in Fig. 1, and the scrapeoff length of the power and particle fluxes was 2.5 cm. The perpendicular diffusion was low (~5% of the Bohm value) and did not affect the results significantly.

The main features of the diverted plasma are illustrated by the plasma parameters along the separatrix for the case where the pump opening was 3.8 cm (20 000 l/sec) (Fig. 2). The neutrals and associated ionization sources are strongly localized near the neutralizer plate. The particle flux from the main plasma is specified as a boundary condition. The particle flux rises rapidly near the plate to 4.7 times the input flux from the main plasma. The electron density rises from $1.15 \times 10^{13}$ cm$^{-3}$ at the divertor throat to a peak of $1.9 \times 10^{13}$ cm$^{-3}$ near the plate, and then falls to $1.3 \times 10^{13}$ cm$^{-3}$ at the sheath boundary. The ion temperature falls from 165 eV at the divertor throat to 21 eV at the sheath boundary. The ion temperature drops more gradually near the divertor walls (Fig. 3). The electron temperature along the separatrix is 30 eV and lower near the walls.

As the pump opening is varied from 6 to 2 cm (Fig. 4), the particle flux at the plate increases from $2.4\times10^{19}$ to $1.36\times10^{20}$ particles $\text{cm}^{-1}$ $\text{sec}^{-1}$. As this flux increases, the electron density at the throat and plate also increases. The neutral pressure at the plate increases from 0.03 to 0.2 Torr. As the densities rise, the electron temperature and ion temperature at the sheath fall by a factor of 4–8.

The key feature of these results is the effect of neutral atoms and molecules recycling from the neutralizer plate. From Eq. (1), we note that since the ionization source, $n_e n_0\langle\sigma v\rangle$, is positive, the total plasma flux, $\Gamma_{xt}=\int nv_x\,dy$, will *increase* from the input value at the divertor throat ($5.84\times10^{18}$/cm sec) to a final value determined by the strength of the ionization source. (Note that in our model $v_x/v_\xi=\Gamma_x/\Gamma_\xi=0.1$.) This increase varied from a factor of 4.2 for the low-density, high-pumping speed case, to a factor of 23.3 in the highest-density case (Fig. 4). Thus, the divertor acts as a "flux amplifier" by forcing the neutrals to recycle many times before they escape through the pump or back to the main plasma.

The existence of an increased particle flux at the sheath boundary at the neutralizer plate implies that the average energy per particle can be lowered, since each plasma ion that enters through the divertor throat has more than one chance to carry energy to the plate before escaping from the divertor as a neutral. The calculations indicate that radiation, ionization, and charge exchange reduce $Q_i$ and $Q_e$ by no more than (10–15)% from the throat to the sheath. Thus with $Q_{ix}\propto T_i\,\Gamma_x$ and $Q_{ex}=2\gamma T_e\,\Gamma_x$ at the sheath, increasing $\Gamma_x$ at the sheath can lower $T_i$ and $T_e$, since $Q_{ix}$ and $Q_{ex}$ at the sheath are very close to their input values. With no neutral recycling, we obtain $T_i=55.4$ eV, $T_e=461$ eV, and $n_e=1.2\times10^{12}$ $\text{cm}^{-3}$. The "extra" recycling of the neutrals can reduce these temperatures to as low as $T_i=11$ eV and $T_e=22$ eV at the sheath (Fig. 4). We also find that the assumption $T_e=\text{const}$ begins to fail for openings of less than 3 cm.

The increased particle flux at the divertor plate not only lowers the temperature there but also raises the density at the plate and back along the field line. This is a consequence of the boundary condition that the flow velocity at the sheath boundary equals the sound speed. Writing $Q_e^{\,\text{sh}}=2\gamma T_e(nv_s)^{\text{sh}}$, we have roughly that $v\propto(T/m)^{1/2}$,

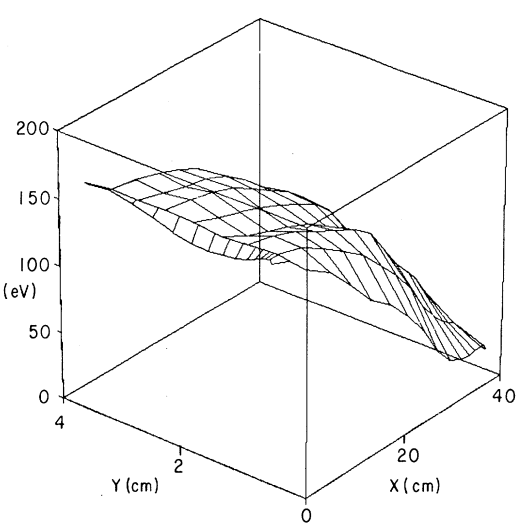


FIG. 3. Ion temperature profile for the modified PDX divertor. $x$ is the distance along the channel and $z$ is the distance across the plasma.

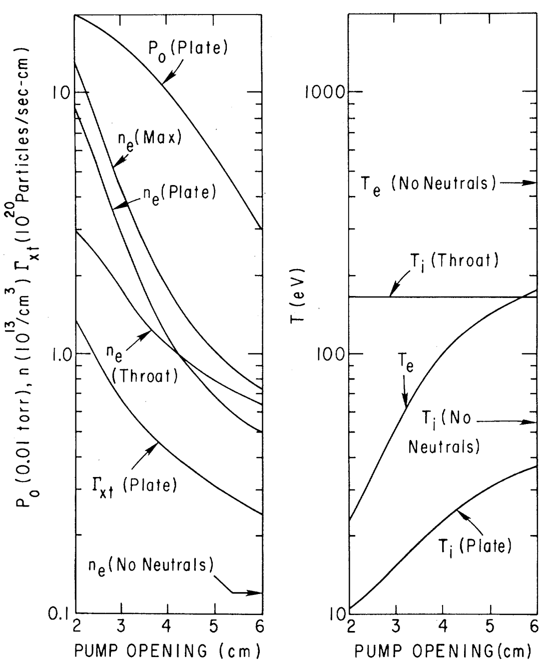


FIG. 4. The neutral pressure $P_0$, the plasma density at the throat and at the plate $n_e$, the ion temperature at the plate $T_i$, the electron temperature $T_e$, and the total particle flux $\Gamma$ at the plate as a function of the pump opening for the modified PDX divertor.

and thus $Q \propto nT^{3/2} \approx$ const at the plate. Dropping $T_e$ from 461 to ~90 eV raises the density from ~$1.2\times10^{12}$ cm$^{-3}$ (the value with no neutrals) to ~$1.3\times10^{13}$ cm$^{-3}$ (Fig. 4), consistent with the $n \propto T^{-3/2}$ scaling. Densities as high as $5\times10^{13}$ cm$^{-3}$ in diverted plasma have recently been reported on Doublet III.[6,7]

A high plasma density in the divertor requires that the neutrals recycle many times. The neutral mean free path in the diverted plasma must be short (i.e., the density must be high), and the "leakage" of neutrals back to the main plasma and down the pump must be minimized by keeping the pump openings and conductances small.

In almost all the cases about 10% of the neutrals escaped back to the main plasma, and about 90% down the pump. The neutral pressure at the plate rose from 0.03 to 0.2 Torr as the pump opening was reduced (Fig. 4). This high pressure is qualitatively similar to the measurements reported by the Alcator group,[8] the Doublet III group,[6,7] and the PDX group.[9] The neutral pressure scales roughly as the square of the throat density consistent with the measurements of Jacobsen.[9] The high neutral pressure implies that even if the geometric pumping speed of the divertor pumping duct is small, the gas throughput would be large.

Lowering the temperature and raising the density in the divertor may offer the possibility of producing a cool, dense plasma layer at the edge of the main plasma outside the divertor, thus "protecting" the wall from the main plasma.

The implication of our results for large fusion reactor experiments of the INTOR type is that by raising the density to the $(2-4)\times10^{13}/\text{cm}^3$ range from $10^{11}-10^{12}/\text{cm}^3$ and lowering the temperatures from 500 to ~20–30 eV the sputtering of wall and neutralizer plate materials can be reduced to tolerable levels. Since the sheath potential could be $\lesssim$60 eV, materials with sputtering thresholds above that could be used. The high neutral pressure at the neutralizer plate means that only modest sized pumping ducts are needed to obtain the necessary gas flow rates of helium and hydrogen. Thus, the realistic possibility of operating poloidal divertors at high densities and low temperatures offers a solution to the problem of handling the particle and heat exhaust of large fusion reactor experiments without generating excessively large impurity levels or requiring excessively large high-speed pumping systems.

The authors are grateful to Dr. G. Bateman, Dr. A. Boozer, Dr. R. Jacobsen, Dr. P. Rutherford, and Dr. J. Weisheit for encouragement and useful discussions. The work was part of the INTOR design effort and was supported by the U. S. Department of Energy Contract No. DE-AC02-76-CH03073.

[1] *International Tokamak Reactor: Zero Phase: Reports of the International Tokamak Reactor Workshops, 1979* (International Atomic Energy Agency, Vienna, 1980).

[2] C. A. Flanagan, D. Steiner, and G. E. Smith, Oak Ridge National Laboratory Report No. ORNL/TM-7777, 1981 (unpublished).

[3] J. Ogden *et al.*, "One-Dimensional Transport Code Modeling of the Divertor-Limiter Region in Tokamaks" (to be published).

[4] D. Heifetz *et al.*, "Monte Carlo Modeling of Neutral Particle Processes in Divertor Devices" (to be published).

[5] D. Meade *et al.*, in Proceedings of the International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, 1980 (unpublished), International Atomic Energy Agency Report No. IAEA-CN-38/X-1.

[6] M. Nagami *et al.*, in Proceedings of the International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, 1980 (unpublished), International Atomic Energy Agency Report No. IAEA-CN-38/0-2.

[7] M. Shimada *et al.*, Phys. Rev. Lett. 47, 796 (1981).

[8] D. Overskei, Phys. Rev. Lett. 46, 177 (1981).

[9] R. Jacobsen, "Preliminary Particle Scoop Limiter Measurements in PDX" (to be published).