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A Cool, High-Density Regime for Poloidal Divertors

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Abstract

Calculations have been performed which demonstrate the possibility of operating poloidal divertors at high densities and low temperatures. This operating regime is caused primarily by ionization of recycling neutral gas near the divertor neutralizer plate which amplifies the input particle flux thereby raising the plasma density and lowering the plasma temperature. Low temperature, high density operation of poloidal divertors would ease the design requirements for future large tokamaks such as INTOR or FED by reducing the erosion rate in the divertor and reducing the neutral density and the associated charge exchange erosion near the main plasma. This regime may have already been observed on several divertor and limiter experiments.

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 megawatts. Applications of simple edge models[3] has 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 large, and the associated erosion due to sputtering also would be large,[4] on the order of 25 cm/year for materials such as iron. As a result of their first year (phase zero) study, one of the topics chosen for further work by the INTOR groups was the design of a poloidal divertor system that could handle large heat loads.

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 to describe the plasma:

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

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

$$\frac{\partial(n_e T_e)}{\partial x} = -neE_x , \tag{3}$$

$$\frac{\partial}{\partial x}\left[nv_x\left(\frac{5}{2}T_i + \frac{1}{2}mv_x^2\right)\right] = nv_x eE_x + S_{E_{ion}}(x,y) + \frac{\partial}{\partial y}\left\{\left[\frac{5}{2}T_i + \frac{1}{2}mv_x^2\right]D\frac{\partial n}{\partial y}\right\}, \tag{4}$$

and

$$\frac{\partial}{\partial x}\left[\frac{5}{2} T_e n v_x + \chi_e \frac{\partial T_e}{\partial x}\right] = -n v_x e E_x + S_{E_e}(x,y) + \frac{\partial}{\partial y}\left[\left(\frac{3}{2} T_e\right) D \frac{\partial n}{\partial y}\right]. \quad (5)$$

S_n, S_p, S_{E_i}, and S_{E_e} are the particle, momentum, and ion and electron energy source terms due ionization, charge exchange, and radiation of the recycling neutral atoms. x is the coordinate along the field line, y is the coordinate perpendicular to the flux surface, D is the cross-field diffusion coefficient, and E_x is the pre-sheath electric field. In most cases of interest, χ_e the electron conductivity is large enough so that T_e is a constant along the field line.

The first three boundary conditions are the particle flux Γ and the electron and ion energy fluxes, Q_e, Q_i, at the divertor throat. The other two boundary conditions are the electron energy flux at the sheath boundary at the neutralizer plate, $Q_e = \gamma\, T_e n v_x$, and v_x, the plasma flow velocity, computed at the sheath boundary from $1/2\ m v_x^2 = 5/6\ T_i + 1/2\ T_e$. The plasma flowing into the sheath flows at the local sound speed. γ is about 2.9 for the case of no secondary electron emission.

The neutral gas source terms are computed 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 reflected either 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 the atomic and molecular hydrogen. In most of the cases of interest, the electron temperature is high enough so that the molecules are ionized, 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.

Calculations were performed for a variety of divertor configurations including the INTOR' design and a new divertor design for PDX.[5] The proposed new PDX divertor geometry is modeled as an axisymmetric rectangular duct with pumping (Fig. 1). The divertor channel is 36 cm long and 6 cm wide. The plasma is 4 cm wide with a 1 cm vacuum gap on each side of the plasma. The pumping chamber is 12 cm by 12 cm with an opening at the bottom that was varied from 2 cm wide to 12 cm wide thus varying the pumping speed at the neutralizer plate from 12,000 ℓ/sec to 64,000 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 3.91×10^{21}/sec corresponding to a particle confinement time of about 50 milliseconds. These conditions were chosen to represent high power neutral injection (8 MW total) and the operation of two divertors, each with two neutralizer plates. 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 ($\sim$ 5% of Bohm) and did not affect the results significantly.

The main features of the PDX model diverted plasma are illustrated by the plasma parameters along the separatrix for the case where the pump opening was 4 cm (21,000 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 five times the input flux from the main plasma. The electron density rises from 2.1×10^{13} cm^{-3} at the divertor throat to a peak of 3.3×10^{13} cm^{-3} near the plate, and then falls to 1.6×10^{13} cm^{-3} at the sheath boundary. The ion temperature falls from 165 eV at the divertor throat to 28 eV at the sheath boundary. The ion temperature drops more gradually near the divertor walls (Fig. 3). The electron temperature along the separatrix is 82 eV and lower near the walls.

As the pump opening is varied from 11.5 cm to 2 cm (Fig. 4), the particle flux at the plate increases from 1.5×10^{19} particles cm^{-1} sec^{-1} to 1.56×10^{20} particles cm^{-1} sec^{-1}. As this flux increases, the electron density at the throat and plate also increases. The neutral pressure at the plate increases from 0.006 torr to 0.35 torr. As the densities rise, the electron temperature and ion temperature at the plate falls by a factor of 5 to 10.

The key feature of these results is the effect of neutral atoms and molecules recycling from the neutralizer plate. From equation (1), we note that since the ionization source, $n_e n_o \langle \sigma v \rangle$, is positive, the plasma flux, $F_x = nv_x$, will <u>increase</u> from the input value at the divertor throat (5.84×10^{18}/cm-sec) to a final value determined by the strength of ionization source. This increase varied from a factor of 2.4 for the low density, high pumping speed case, to a factor of 34.5 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 plate. Thus with $Q_{ix} \propto T_i F_x$ and $Q_{ex} = 2\gamma T_e F_x$ at the plate, increasing Γ_x at the plate can lower T_i and T_e, since Q_{ix} and Q_{ex} at the plate 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 × 10^{12} cm^{-3}. The "extra" recycling of the neutrals can reduce these temperatures to as low as T_i = 11 eV and T_e = 19 eV at the plate (Fig. 4).

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 $Q_e = 2\gamma T_e n v_s$, we have roughly that $v \propto (T/m)^{1/2}$, and thus $Q \propto nT^{3/2}$ ≈ constant at the plate. Dropping T_e from 461 eV to ~ 100 eV raises the density from ~ 1.2 × 10^{12} cm^{-3} (the value with no neutrals) to ~ 1.3 × 10^{13} cm^{-3} (Fig. 4), consistent with the $n \propto T^{-3/2}$ scaling. Densities as high as 5 × 10^{13} cm^{-3} in diverted plasmas have recently been reported on Doublet III.[6]

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 PDX 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 0.006 torr to 0.35 torr as the pump opening was reduced (Fig. 4). This high pressure is qualitatively similar to the measurements reported by the Alcator group,[7] the Doublet III group,[6] and PDX group.[8] The neutral pressure scales roughly as the square of the throat density consistent with the measurements of R. Jacobsen.[8] The high neutral pressure implies that even if the geometric pumping speed of 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 INTOR calculations were done for a 30 cm wide and 60 cm long divertor. By suitably reducing the geometric pumping near the neutralized plate, high density operation can be achieved, raising the density to the 2-4 $\times 10^{13}/cm^3$ range from $10^{11} - 10^{12}/cm^3$ and lowering the temperatures from 500 eV to ~ 20-30 eV. With such temperatures the sputtering of wall and neutralizer plate materials can be significantly reduced, since the sheath potential could be $\lesssim$ 60 eV and materials with sputtering thresholds above that could be used. The plasma density is high enough so almost all the neutrals go down the pump with very few returning to the plasma to cause sputtering of the first wall. 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. The strong localization of the neutral recycling to the region near the neutralizer plate also implies that there is a possibility that the INTOR divertor could be shorter than 60 cm, perhaps only as long as 20-30 cm, which would greatly ease divertor design problems. 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.

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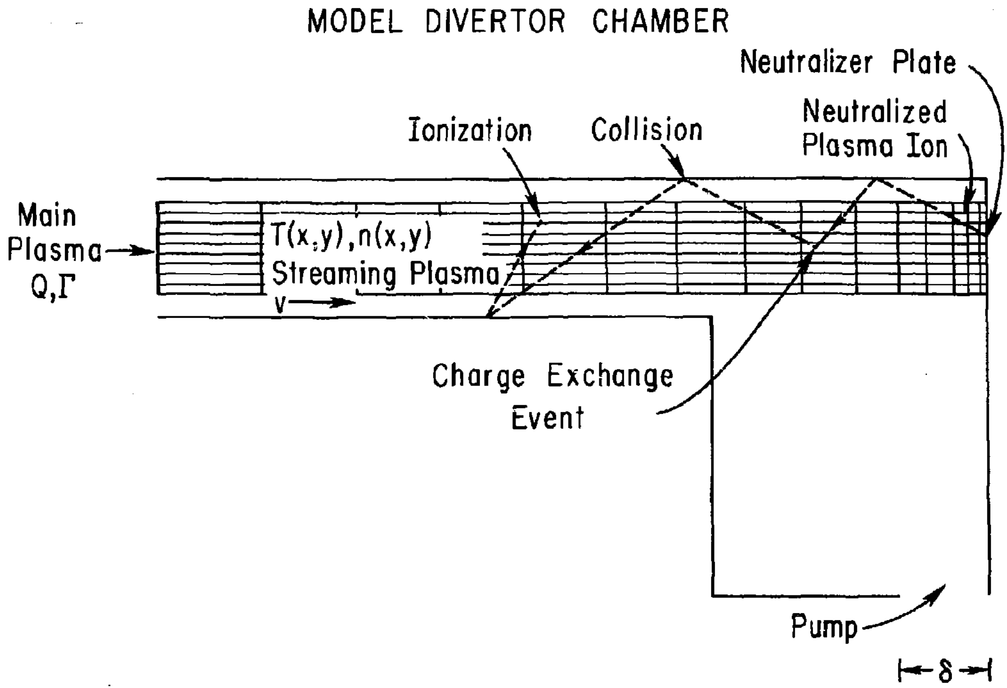

Fig. 1 Model divertor chamber.

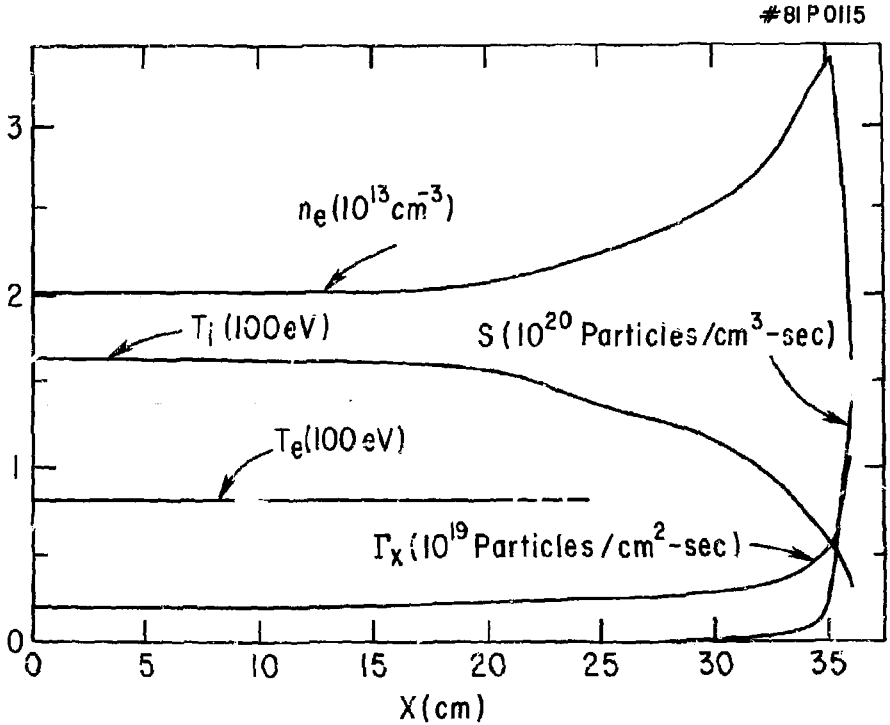

Fig. 2 Calculated plasma parameters along the separatrix in the modified PDX divertor for a pump opening of four centimeters.

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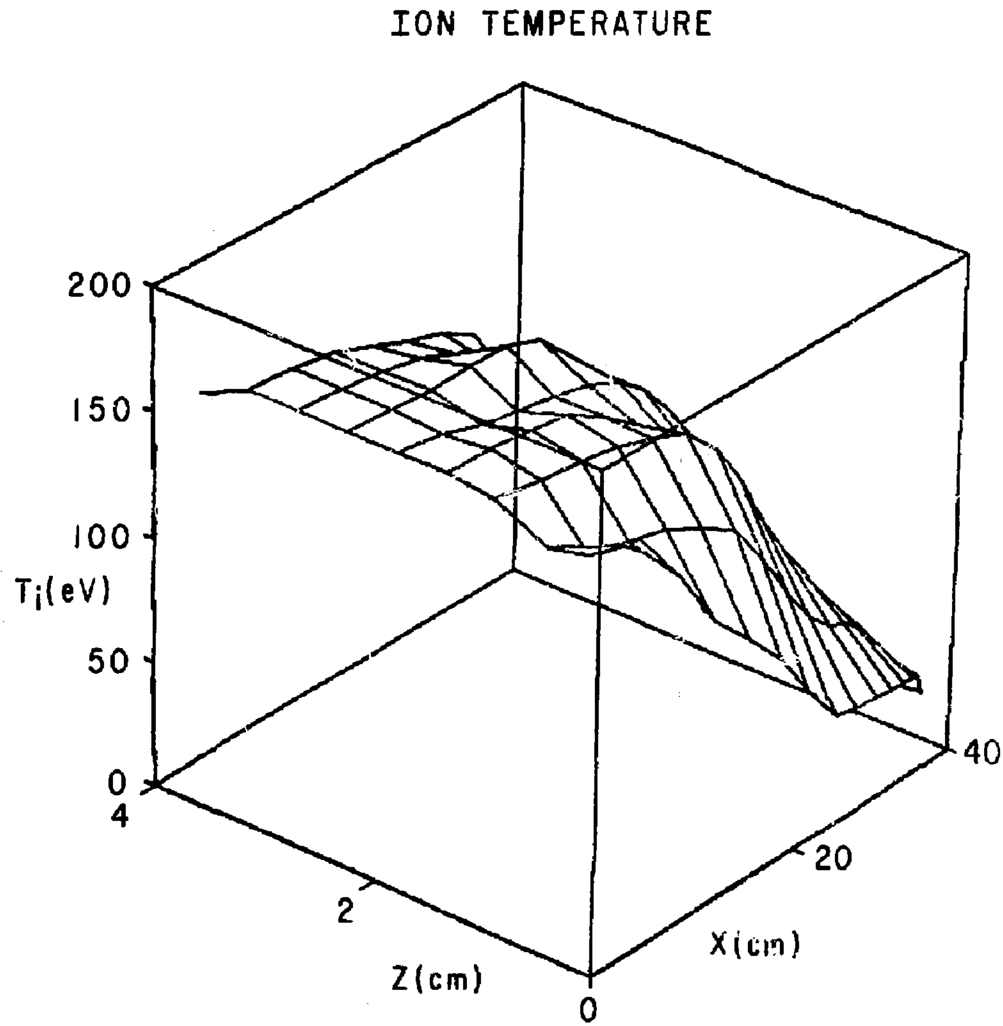

Fig. 3 Ion temperature profile for the modified PDX divertor. X is the distance along the channel and Z is the distance across the plasma.

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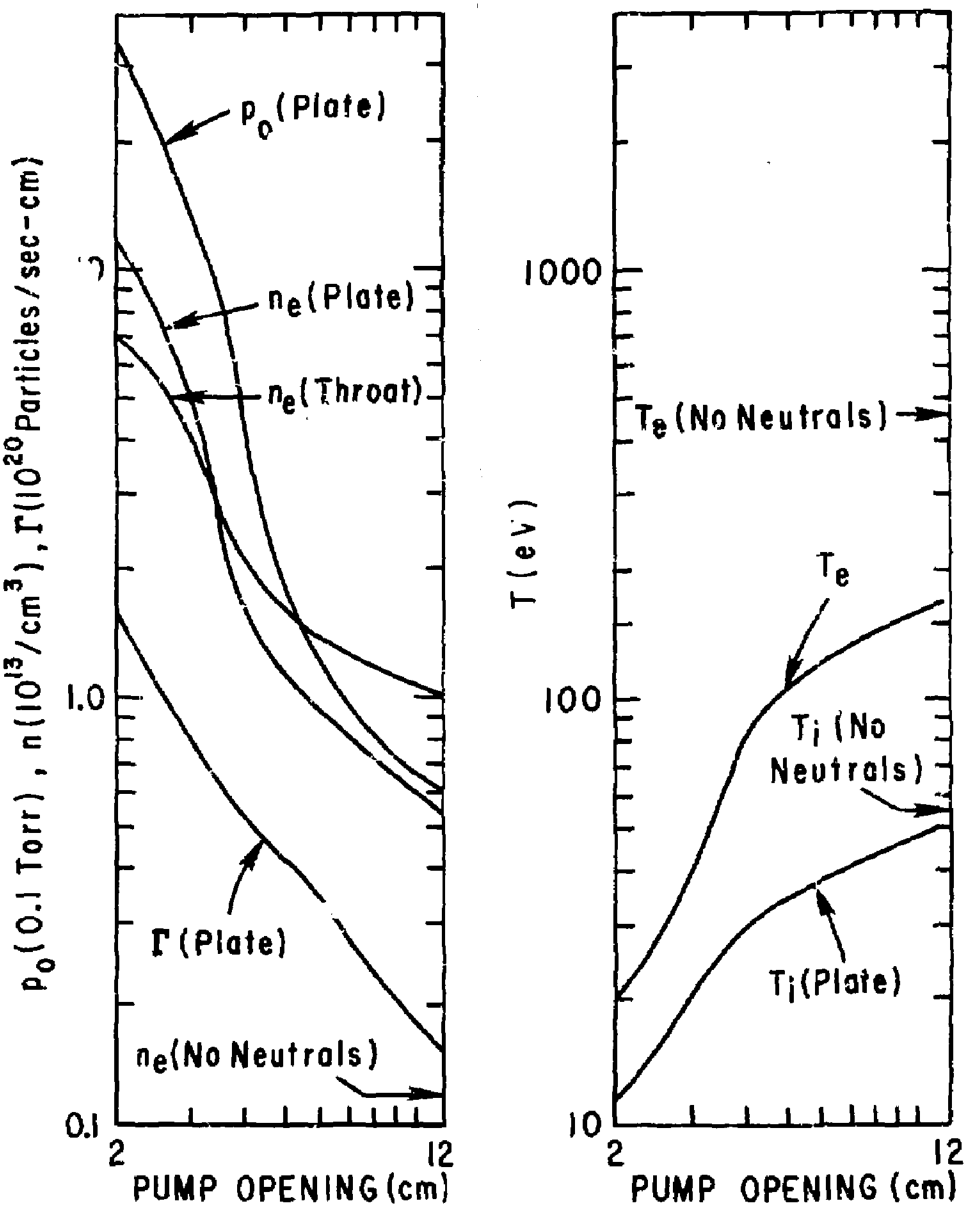

Fig. 4 The neutral pressure P_o, the plasma density at the throat and at the plate n_e, the ion temperature at the plate T_i, and the electron temperature T_e, and the total particle flux Γ at the plate as a function of the pump opening for the modified PDX divertor.