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Performance of the INTOR Poloidal Divertor*

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Abstract

The next generation of large tokamak experiments is expected to have large particle and heat outfluxes ($\sim 10^{23}$ particles/sec and 80 MW). These outfluxes must be controlled to provide adequate pumping of the helium "ash" and to minimize the sputtering erosion of the vacuum vessel walls, limiters, and neutralizer plates. A poloidal divertor design to solve these problems for INTOR has been done using a two-dimensional code which models the plasma as a fluid and solves equations for the flow of particles, momentum and energy, and calculates the neutral gas transport with Monte-Carlo techniques. These calculations show that there is a regime of operation where the density in the divertor is high and the temperature is low, thus easing the heat load and erosion problems. The neutral pressure at the plate is high, resulting in high gas throughputs, with modest pumping speeds.

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Computational models have been used to assist in the design of a poloidal divertor system for INTOR. The divertor is to be used to control the expected particle and heat outflux from INTOR of $\sim 10^{23}$ particles/sec and 80-100 MW of thermal plasma energy. The divertor must be able to handle the heat load without excessive cooling requirements for the neutralizer plates and divertor walls, and without large erosion rates for the divertor walls and neutralizer plates. Large erosion rates would lead to unacceptably large impurity levels in the main plasma and require frequent replacement of the divertor structure. 80-100 MW of fusion thermal power corresponds to a production of $\sim 2 \times 10^{20}$ alpha particles/sec. This helium ash must be removed from the discharge to facilitate long pulse ($\gtrsim$ 50 sec) operation.

Simple estimates of edge conditions for INTOR parameters yield low densities ($5 \times 10^{11}/cm^3$) and high temperatures (1,000 eV). An electron temperature of 1,000 eV implies a sheath drop at a limiter or neutralizer plate of $\sim$ 3,000 eV with large erosion rates ($\sim$ 25 cm/year for iron). A low plasma density at the edge means that the first wall is not shielded from the hot central plasma. In addition, a low edge plasma density means that the neutral pressure will be low for helium and hydrogen pumping. The purpose of the divertor is then to control the edge plasma so that the heat and particle outfluxes can be handled with minimum erosion problems and reasonable pumping speeds.

A two-dimensional model was constructed to examine these questions. The neutral gas transport is calculated using Monte-Carlo techniques [1]. The collisions of neutrals and ions with the walls are handled using experimental reflection data. The relevant atomic collision processes for D^o, T^o, DD^o, DT^o, TT^o, He^o, D^+, T^+, DD^+, DT^+, TT^+, He^+, He^{++}, and e^- are included. The code is thus able to calculate ionization, excitation and charge-exchange source terms for a plasma calculation. It also calculates the neutral gas flows and pressures and the wall heat loads and sputtering (erosion) rates.

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:

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

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

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

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

and

$$\frac{\partial}{\partial x}\left[\frac{5}{2}\,T_e nv_x + \chi_e\,\frac{\partial T_e}{\partial x}\right] = -nv_x eE_x + S_{E_e}(x,z) + \frac{\partial}{\partial z}\left[\left(\frac{3}{2}\,T_e\right) D\,\frac{\partial n}{\partial z}\right], \tag{5}$$

where 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. x is the coordinate along the field line, z 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, $Q_e = \gamma 2 T_e n v_x$, 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. The constant γ is about 2.9 for the case of no secondary electron emission.

The calculations were performed for conditions appropriate to a single null divertor with the heat flux of 40 MW and a particle flux of 3×10^{22} particles/sec into one divertor (Fig. 1). With these conditions, setting the neutral source terms to zero (no ionization or charge-exchange) yields $T_e \sim 1{,}500$ eV, $n_e \sim 2 \times 10^{11} cm^{-3}$ and $P_o \sim 10^{-5}$ torr at the neutralizer plate. Using the self-consistent source terms from the neutral gas computation lowers T_e to ~ 40 eV, and raises n_e to $\sim 2.5 \times 10^{13} cm^{-3}$ and p_o to ~ 0.1 torr (Fig. 2,3). T_i drops along the field line from ~ 160 eV to 20 eV at the plate. The ionization source is localized near the plate. The particle flux increases by a factor of twenty from the throat to the plate. The particle flow velocity is about 10% of the sound speed at the throat and increases to the sound speed at the plate (Fig. 4).

The electron density rise is largest along the separatrix, and near the corner away from the pump (Fig. 5). The ion temperature profile is flat at the throat (Fig. 6). The neutral pressure profile drops slightly near the pump, but is still ~ 30 millitorr at the pump opening (Fig. 7). About 90% of the input power is still dumped on the neutralizer plate and the other 10% on the divertor walls. The total erosion rates of the neutralizer plate and divertor walls are about equal.

The high density operation is due to the rapid recycling of plasma and neutrals at the divertor plate. This can be understood from the continuity equation,

$$\frac{\partial(nv)}{\partial x} = S_{ion} = n_o n_e \langle \sigma v \rangle_{ionization} .$$

Since S_{ionize} is positive, the flux will increase as the neutralizer plate is approached. If the neutrals cannot easily escape down the pump or return to the main plasma, they will recycle many times before escaping. In our case, the flux at the plate is nineteen times the input flux (Fig. 2) and thus, the divertor acts as a particle "flux amplifier." T at the plate is reduced since $Q \propto Tnv$. $T \propto Q/nv$ implies that T drops as $F = nv$ rises. Since, at the plate $v \approx (T/m)^{1/2}$ and $Q \propto Tn\ (T/m)^{1/2} \propto nT^{3/2}$, $nT^{3/2}$ is a constant, and lowering T raises n. The large neutral pressure comes from the high recycling flux at the plate.

$v \sim 0.1\ v_s$ at the throat is roughly consistent with the DIVA measurements [3]. The high neutral pressure is roughly consistent with the Alcator results [4], PDX results [5], and UCLA results [6]. Densities as high as $\sim 10^{14} cm^{-3}$ in a diverted plasma have been observed on D-III [7]. The particle flow rate down the pump is 3×10^{22} particles/sec. With $n_{He}/n_e \sim 0.05$, we need to pump only 4×10^{21} particles/sec, so we could reduce the geometric pumping speed of our duct to ~ 25,000 l/sec.

Our calculations show no helium enrichment. In some of the highest density cases, significant de-enrichment is found which may raise the pumping requirements above 25,000 l/sec.

Lowering the electron temperature from 1,500 eV to ~ 40 eV may allow the use of high Z neutralizer plates such as tungsten. However, reducing T_e just a little farther would open up the use of medium and even low Z materials. The high density divertor plasma will extend back to the edge of the main plasma and scrape-off layer, possibly providing a cool, dense, plasma blanket to shield the first wall from the plasma. Containing the neutrals near the neutralizer plate will reduce the erosion near the divertor throat. Since the neutral ionization and other effects are localized near the plate, the possibility exists that the divertor channel would be made shorter than 70 cm, perhaps as short as 30 cm.

Acknowledgments

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References

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Figure Captions

Fig. 1. Geometry for the INTOR divertor calculation.

Fig. 2. Plasma conditions along the field line for the center of the divertor, $Q = 40$ MW, $\Gamma = 3 \times 10^{22}$ particles/sec.

Fig. 3. Plasma flow velocity along the field line for the center of the divertor.

Fig. 4. Neutral pressure along the center of the divertor.

Fig. 5. Density profile in the divertor.

Fig. 6. Ion temperature profile in the INTOR divertor.

Fig. 7. Neutral pressure profile in the INTOR divertor.

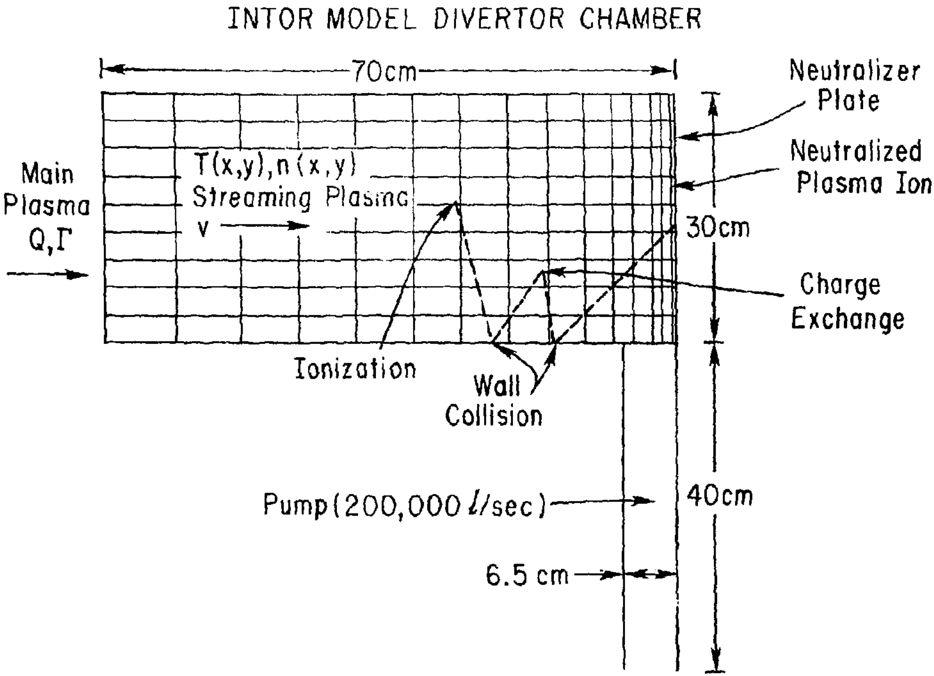
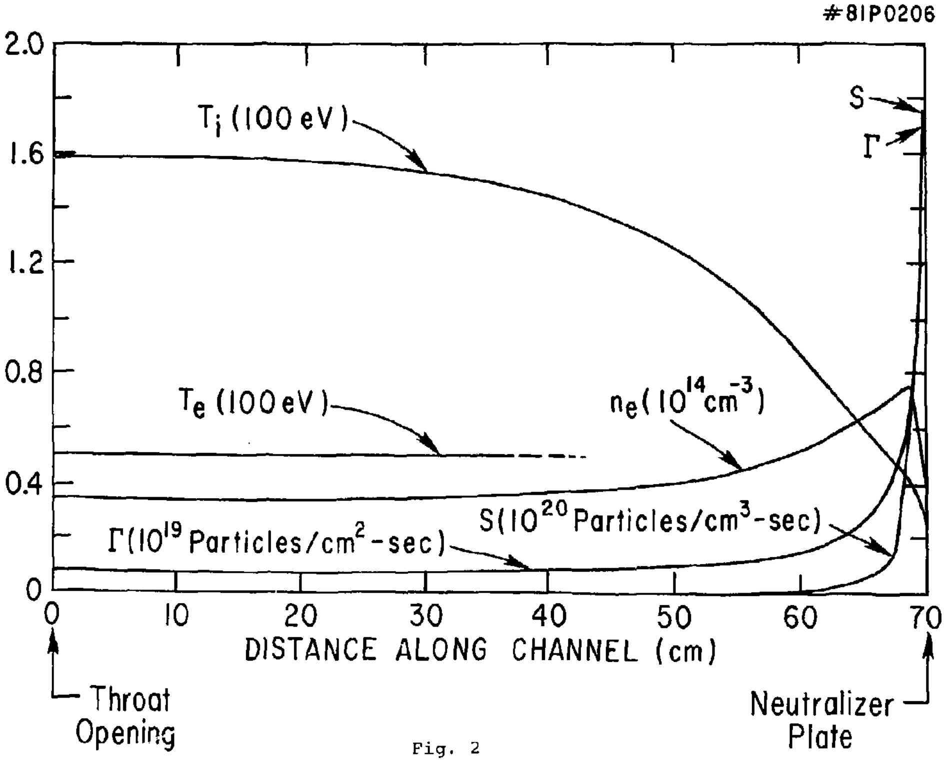

INTOR MODEL DIVERTOR CHAMBER
70cm
Neutralizer Plate
Neutralized Plasma Ion
Main Plasma
Q,Γ
T(x,y),n(x,y)
Streaming Plasma
v
30cm
Charge Exchange
Ionization
Wall Collision
Pump(200,000 l/sec)
40cm
6.5 cm

Fig. 1



#81P0206
2.0
1.6
1.2
0.8
0.4
0
S
Γ
Ti (100 eV)
Te (100 eV)
ne (10^14 cm^-3)
S(10^20 Particles/cm^3-sec)
Γ(10^19 Particles/cm^2-sec)
0
10
20
30
40
50
60
70
DISTANCE ALONG CHANNEL (cm)
Throat Opening
Neutralizer Plate

Fig. 2

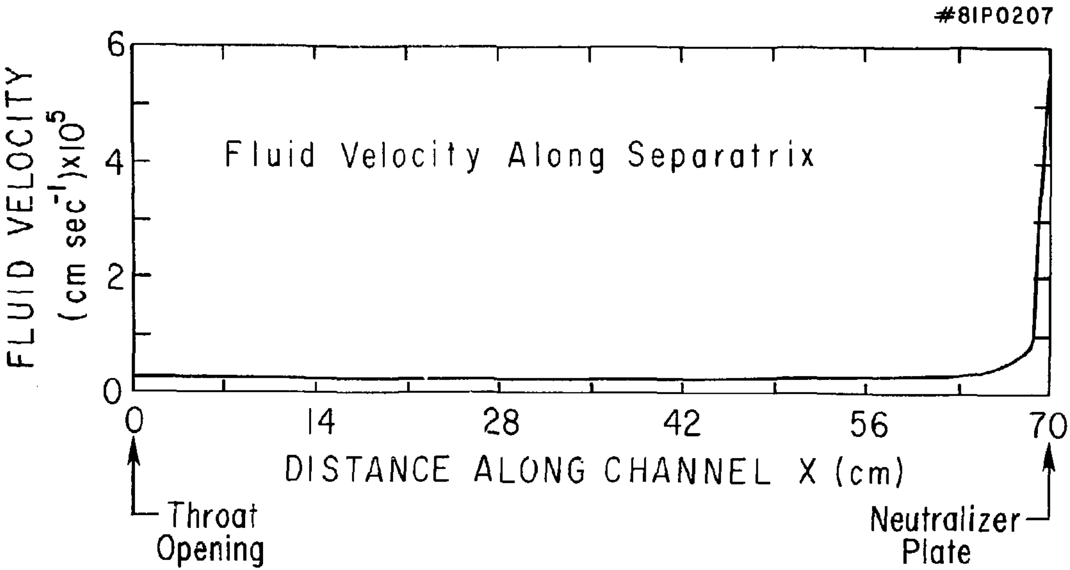

#81P0207
FLUID VELOCITY
(cm sec^{-1})x10^{5}
6
4
2
0
Fluid Velocity Along Separatrix
0
14
28
42
56
70
DISTANCE ALONG CHANNEL X (cm)
Throat
Opening
Neutralizer
Plate

Fig. 3

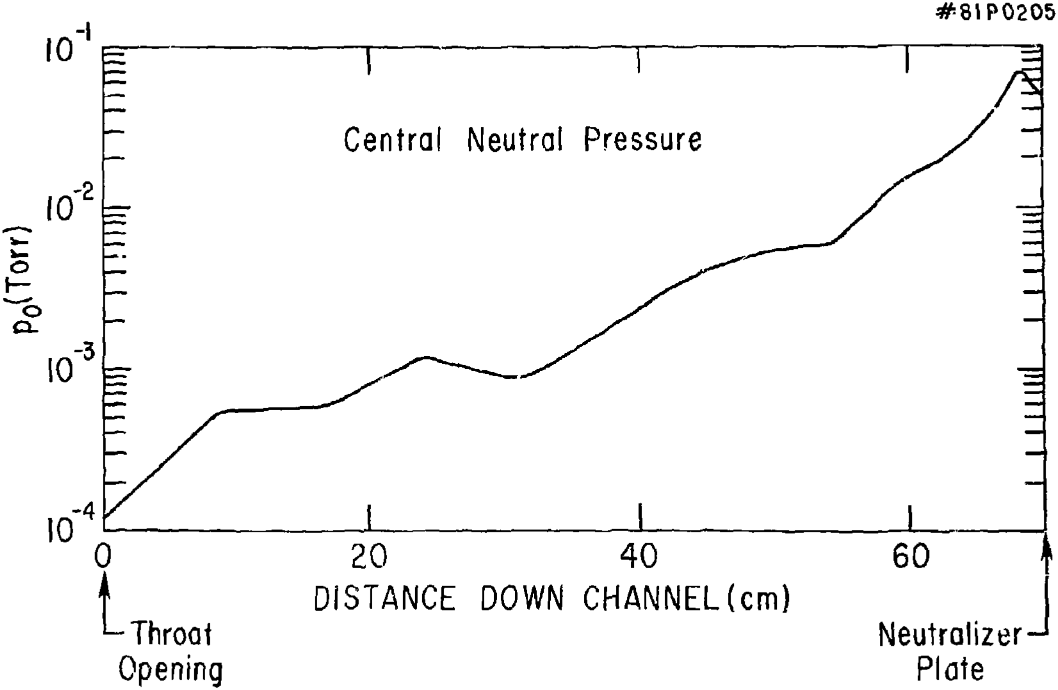
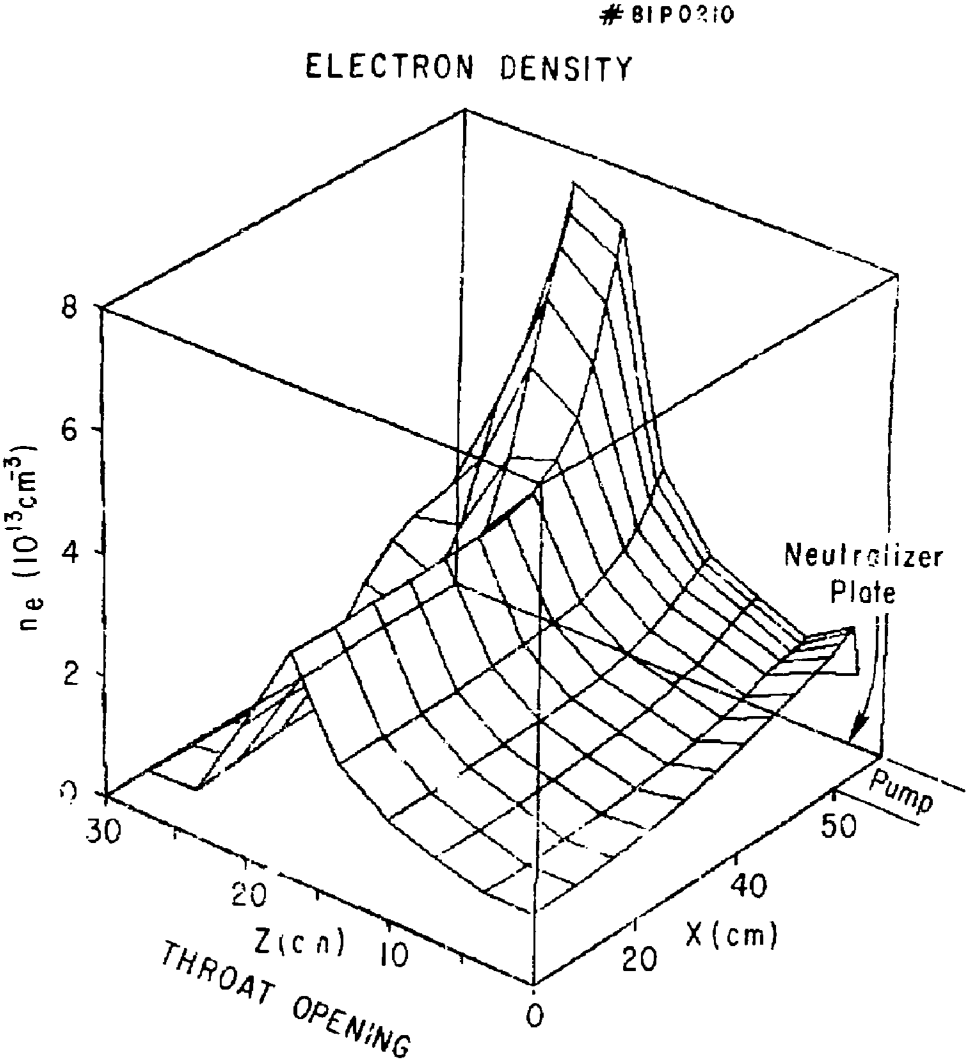

#81P0205
Central Neutral Pressure
p_0(Torr)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
DISTANCE DOWN CHANNEL (cm)
Throat Opening
Neutralizer Plate

Fig. 4



#81P0210
ELECTRON DENSITY
8
6
4
2
0
n_e ($10^{13}cm^{-3}$)
Neutralizer
Plate
Pump
30
20
Z(cm)
10
THROAT OPENING
0
20
X(cm)
40
50

Fig. 5

#81P0208

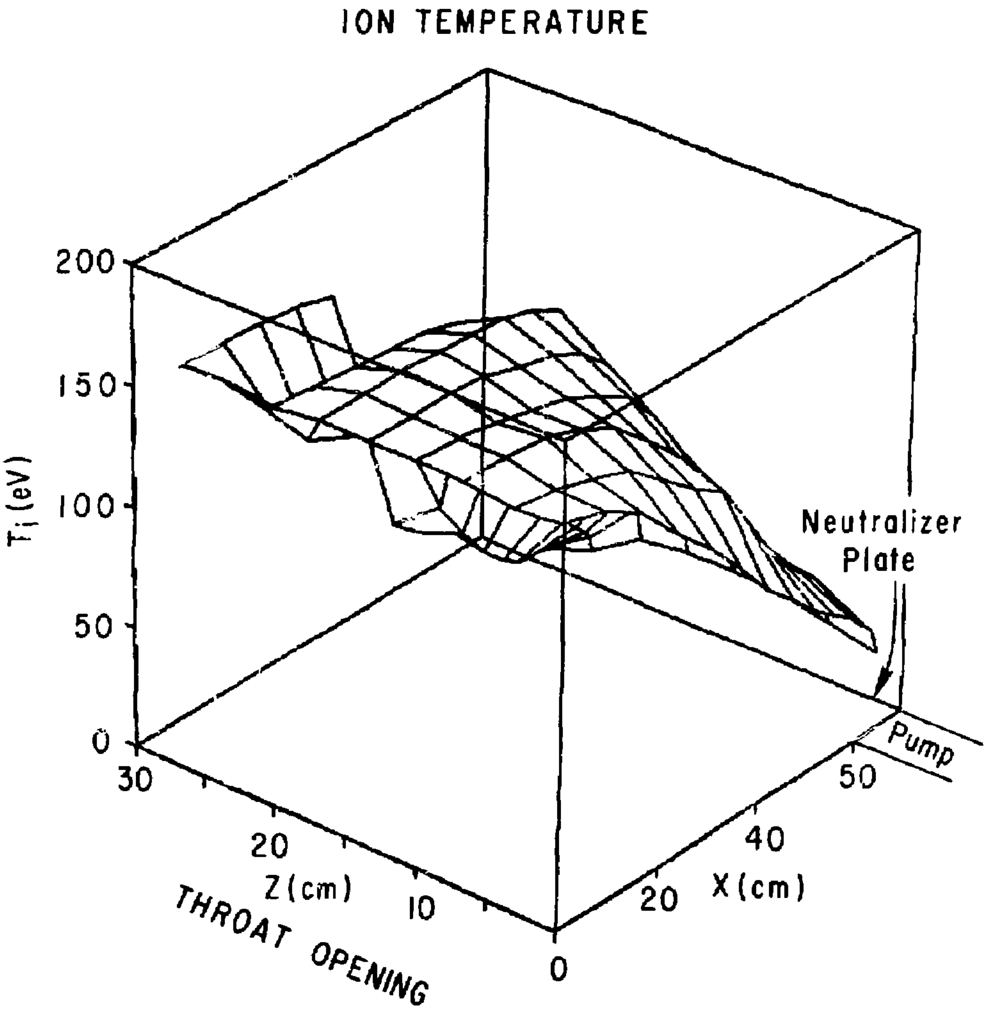


Fig. 6

81P0209

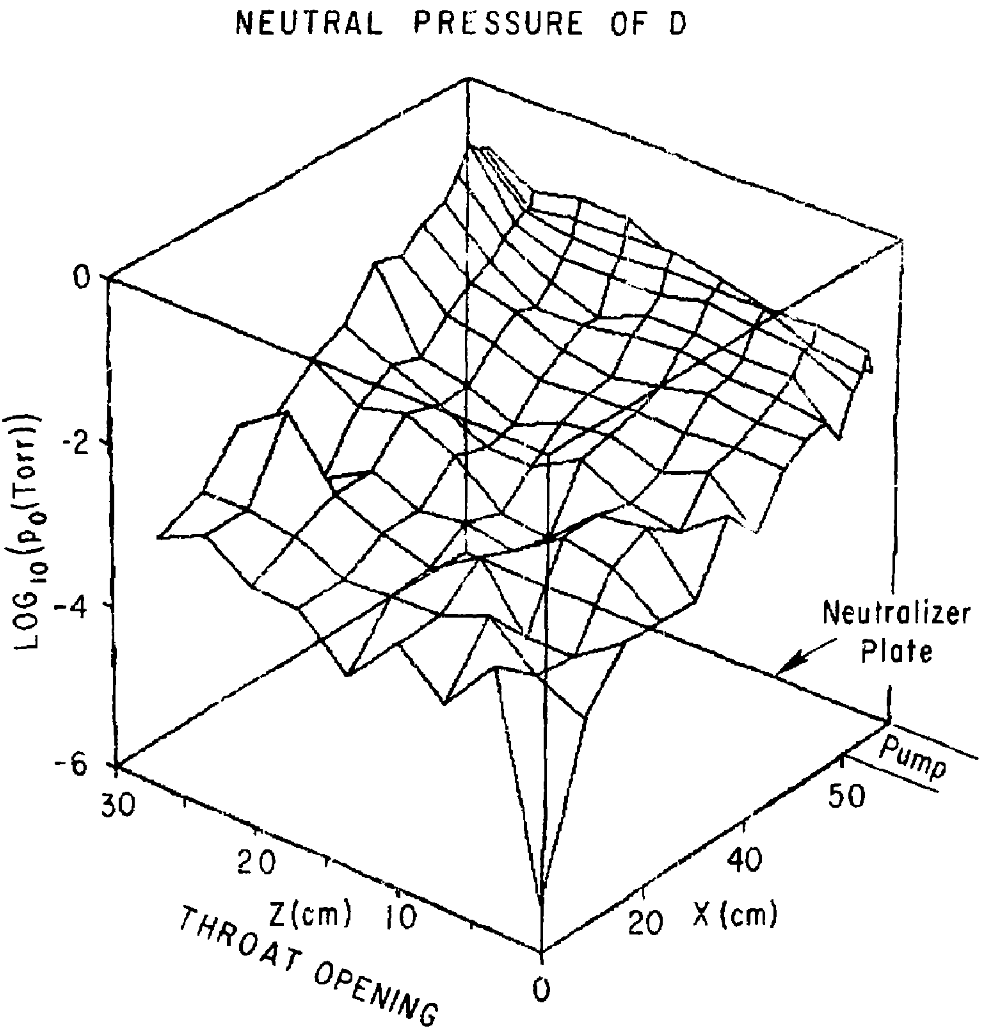


Fig. 7