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GASEOUS DIVERTOR SIMULATION IN AN ARC-JET DEVICE

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ABSTRACT

The first experimental simulation of the gaseous tokamak divertor is presented. Significant results are (i) neutral gas at a pressure of a few mTorr is sufficient to absorb the entire localized flux of plasma thermal energy and redistribute it over a wide area; (ii) elastic ion-neutral collisions constitute the main energy absorbing process (at $T_{e,i} \lesssim 5$ eV), and (iii) a large pressure difference between divertor and main plasma chamber is maintained by plasma pumping in the connecting channel.

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The handling of large heat flux is one of the major difficulties in the design of particle removal in a fusion reactor. For example, calculations on the proposed reactor-scale tokamak, INTOR, indicate that the rate of thermal energy flow into the divertor chambers would be ~100 MW[1]; with conventional collector plates this would produce an unacceptable rate of surface erosion. One way of coping with this problem would be to dump the energy into a quantity of neutral gas.[1-3] The essential features of such a gaseous divertor are the spreading of the energy flux over a comparatively large area of the chamber wall, and sufficient plasma pumping to confine the neutral gas almost entirely to the divertor chamber. An important aspect is that collisions with the gas molecules keep reducing the plasma density and temperature to the point where recombination rapidly eliminates the remaining plasma, thereby removing the need for collector plates.

Here we describe an experiment on the dumping of a drifting plasma into a volume of neutral gas; it is the first simulation experiment to verify the physical principles underlying the proposed gaseous divertor section of a tokamak. The most important results are (i) neutral gas at a pressure of a few mTorr ($\ll n_e T_e$) can absorb the entire localized flux of plasma energy and redistribute it over a wide area of the divertor chamber wall; (ii) at the low temperatures typical of scrape-off plasmas in divertors ($\lesssim$ 5 eV), elastic ion-neutral collisions are shown here to be the main absorption process; and (iii) a large pressure difference ($\sim n_e T_e$) between divertor and main plasma chamber can be maintained by plasma pumping in the connecting channel.

The experiment was performed in the Princeton QED device,[4] shown in Fig. 1. A short 200 A hydrogen arc provides a 1.5 cm diameter H^+ plasma which drifts along the magnetic field (~ 2 kG), through two limiters, into the divertor chamber D. The magnetic field is fairly uniform ($\pm$ 7%) over the first 70 cm in D. At the point of entry, L_2, the density and electron temperature ($\sim 5 \times 10^{13}$ cm^{-3} and $\sim$ 5 eV) are typical of the cool plasma in the divertors of large tokamaks such as PDX and Doublet III. The diagnostics in D include Langmuir probes for obtaining profiles of n_e and T_e, and calorimeter plates $C_{A,R}$ for determining the axial and radial energy flux (by measurement of the rate of heat conduction along the plate support rods). Plate C_A (diameter 7.5 cm) can be moved axially over the range $z > 30$ cm, measured from L_2, while C_R (diameter 4 cm) is positioned well outside the plasma at $r = 4$ cm and can be moved axially from $z = 10$ cm. A gas sampling probe, connected to a quadrupole mass spectrometer, is also available for measuring the local concentration of any gaseous element introduced into the arc-jet to form impurity ions.

From Langmuir probe measurements and the assumption that the plasma drifts at the ion acoustic speed, a typical computed drift rate of the plasma thermal energy into the chamber D was $\sim$ 500 W. Axial and radial energy collection rates $\Gamma_{z,r}$ were measured by plates C_A and C_R at different distances z and different gas pressures P_D. The minimum value of P_D was 2.5 mTorr, set by the influx of plasma particles and the pumping speed; higher values were obtained by feeding hydrogen gas into D. The main result is shown in Fig. 2, namely that increasing P_D to about 5 mTorr reduced the axial energy flux at $z = 70$ cm by two orders of magnitude, to a value comparable to the average radial flux. Furthermore, by integrating the energy flux over the cylindrical surface bounded by L_2 and the two calorimeter plates, we obtained a total power of $\sim$ 400 W (in reasonable agreement with the computed input of 500 W) which remained almost constant as P_D was changed from 2.5 to 4.6 mTorr.

The loss in axial energy flux is compensated by the rise in radial energy flux: the neutral gas acts as an effective absorber and distributor of plasma energy.

As the gas pressure P_D is raised above 10 mTorr, without changing the upstream plasma conditions, the plasma column terminates before reaching C_A: the length of the plasma column in D begins to shorten markedly and the energy flux to C_A and C_R rapidly becomes negligible. Finally, the gas pressure becomes sufficient to push the plasma out of the chamber D and remove the pressure difference between D and M almost completely. The position of the plasma-gas interface, whether in D or M, can be controlled by varying either the gas pressure or the plasma pressure, $n_e T_e$. The interface itself had a steady visual appearance; no large scale oscillations were seen. Probe measurements show that there is a rapid decrease in T_e as the plasma reaches this interface, to values < 0.2 eV, over a distance of 1 or 2 cm. Unpublished data on collision cross-sections[5] indicate that elastic collisions between H^+ ions and hydrogen molecules should be the dominant particle interaction at $T_{e,i} \lesssim 5$ eV.

The dominance of elastic ion-neutral collisions is evident from two different sets of measurements. Qualitative support comes from our observation that argon gas was a less effective collector of plasma energy than hydrogen gas, even though the ionization cross-section, for example, is larger for argon than for hydrogen; the mass coupling term $m_1 m_2/(m_1+m_2)^2$ counts against argon in the case of elastic collisions. More important, however, is the quantitative evidence provided by measurements of the exponential rate of decay of n_e and T_e with distance z, obtained at different values of the parameter Ω_i/ν_{in} (or B/P_D), where Ω_i is the ion gyro-frequency and ν_{in} the ion-neutral collision frequency. The quantities $n_e(z)$ and $T_e(z)$ are combined to produce an axial decay length ℓ of the plasma pressure $P(z) = n_e(z)\ T_e(z)$, which is plotted against B/P_D in Fig. 3. These data are now compared with a simple fluid model containing ion-neutral collisions.

The relevant continuity and one-fluid momentum equations are

$$\frac{\partial}{\partial z}\ (nv) = \frac{1}{r}\frac{\partial}{\partial r}\ [\frac{D_\perp}{T_e + T_i}\ r\ \frac{\partial P}{\partial r}\ ]\ , \qquad (1)$$

$$\frac{\partial P}{\partial z} = -\ m_i\ \nu_{in}\ nv\ , \qquad (2)$$

where $P = P\ (r,z)$ is the plasma pressure, v is the plasma drift velocity along the z direction and $D_\perp$ is the cross field diffusion coefficient:

$$D_\perp = \frac{T_e + T_i}{m_i}\ \frac{\nu_{in}}{\Omega_i^2[1 + (\nu_{in}^2/\Omega_i^2)]}\ . \qquad (3)$$

Here we have assumed that $D_\perp$ is set by the radial drift of the ions because of the short circuiting effect of the metal plates at both ends of the plasma column[6]; the electron fluid is in good contact with both ends at the pressures (< 10 mTorr) corresponding to Fig. 3. With $\nu_i/\Omega_i \ll 1$ (as in the present experiment), the continuity equation leads to a solution for the pressure,

$$P = P_o\ J_o\ (\frac{r}{a})\ e^{-z/\ell}\ , \qquad (4)$$

where a is the plasma radius and ℓ is the axial decay length given by the expression

$$\ell = \frac{a}{2.405}\ \frac{\Omega_i}{\nu_{in}}\ . \qquad (5)$$

Estimating ν_{in} from published values of $\langle\sigma v\rangle_{in}$,[5] we find that Eq. (5) corresponds to the straight line in Fig. 3 to within 30%. Radial profiles P(r) show good agreement with the $J_o(r/a)$ form given in Eq. (4).

Having established the effectiveness of neutral gas as an energy sink, we turn to the question of the effectiveness of plasma pumping in preventing the gas from streaming into the main plasma chamber.[7-9] Attaching a cylindrical metal tube (diameter 2 cm, length 7.5 cm) to the left hand face of limiter L_2, to simulate a divertor channel, we have measured the pressure difference, $P_D - P_m$, between the two chambers as the hydrogen feed rate (and hence P_D) is increased. As shown in Fig. 4(a), this difference reaches values as large as 400 millitorr ($\lesssim n_eT_e$, as required by momentum conservation) before the plugging of the tube by the plasma suddenly breaks down and neutral gas streams through from D to M, leaving a relatively small pressure difference set by the tube conductance.

Replacing the above tube with a much larger one (diameter 10 cm, length 90 cm) attached to the right hand face of L_2, we have used the gas sampling probe to measure the partial gas pressures of hydrogen (the main plasma ion species), argon, and helium (introduced into the arc-jet as impurities) at different distances along the tube. Figure 4(b) contains typical data for neutral hydrogen, showing the pressure decreasing exponentially as one moves upstream from the plasma-gas interface at $z \simeq 13$ cm. The exponential pressure decay lengths of the three species of molecule are found to be in the ratio ℓ_{He}: ℓ_{H_2}: $\ell_{Ar} \equiv 1.4$: 1.0: 0.7. These are ordered in the same way as the respective reciprocal rate coefficients, $\langle\sigma v\rangle^{-1}$, for elastic collisions with H^+ ions, namely 2: 1: 0.7,[10] which again emphasizes the dominance of ion-neutral collisions at these low electron temperatures. This means that, in comparison with chamber M, there is enrichment of Ar and diminishment of He in chamber D.

In conclusion, crucial features of proposed gaseous divertor operation have been demonstrated: neutral gas, confined to a divertor chamber by plasma pumping, can provide an effective cushion and cooling mechanism to receive and disperse highly localized energy flux. Although the temperature of the scrape-off plasma in a tokamak would be higher initially, radiative losses in the neutral gas would bring it rapidly into the regime studied in this experiment. Such divertor operation would offer the further advantages of eliminating costly collector plate structures and easing the more severe pumping requirements of a lower pressure regime.

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FIGURE CAPTIONS

Fig. 1. Experimental arrangement configuration. A, arc-jet plasma source; Q, plasma column; $L_{1,2}$, limiters; $C_{A,R}$, calorimeters; M, main plasma chamber; D, divertor chamber; $P_{M,L}$, pressure gauges; $P_{1,2,3}$, pumps.

Fig. 2. Energy-collection rates vs gas pressure: Γ_z, axial collection by C_A at $z = 70$ cm; Γ_r, radial collection by C_R at $z = 30$ and 10 cm.

Fig. 3. Plasma pressure decay length (along z) vs $(a/2.405)\ \Omega_i/\nu_{in}$. Solid line corresponds to the theoretical curve for $a = 1.2$ cm.

Fig. 4. (a) Gas pressure in divertor, P_D, and in main chamber, P_M, vs hydrogen-gas feed rate, showing feed rate change (hatched) for plugging of short connecting channel by plasma. (b) Gas pressure in long connecting channel vs axial distance.

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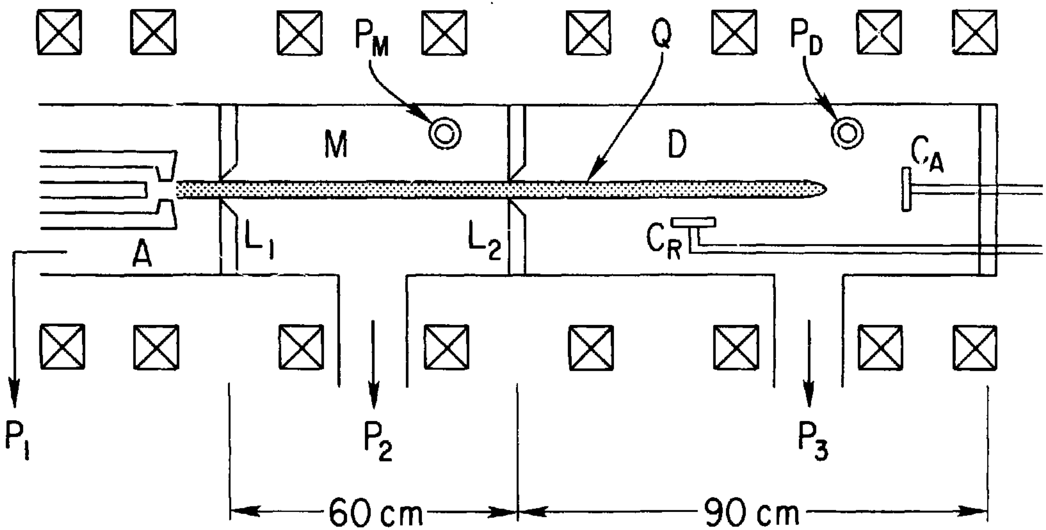
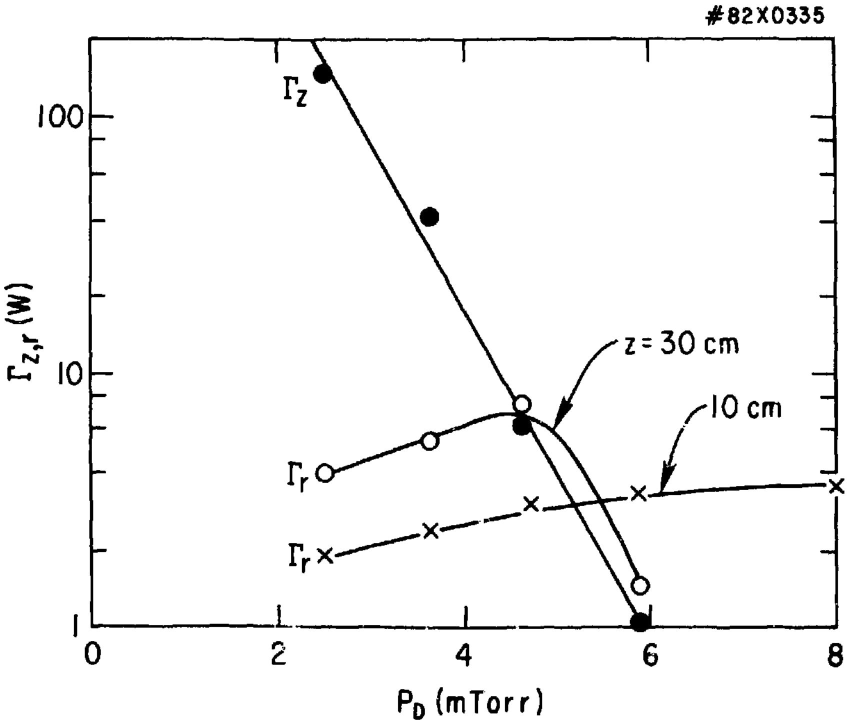


Fig. 1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Γ_Z
Γ_r
Γ_r
z = 30 cm
10 cm
100
10
1
0
2
4
6
8
$\Gamma_{z,r}$ (W)
P_D (mTorr)

Fig. 2

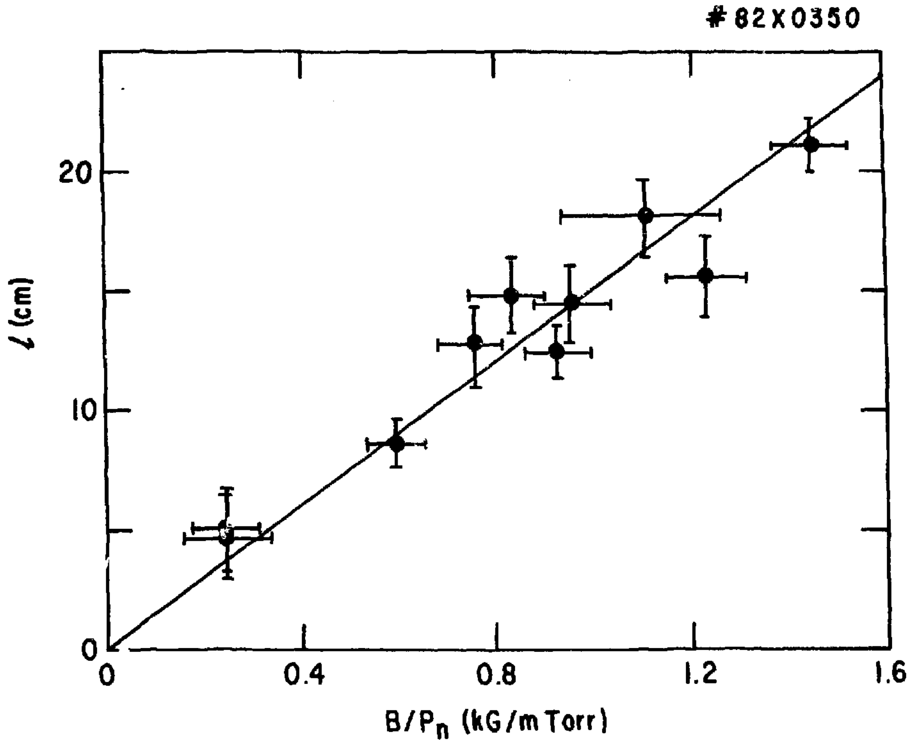
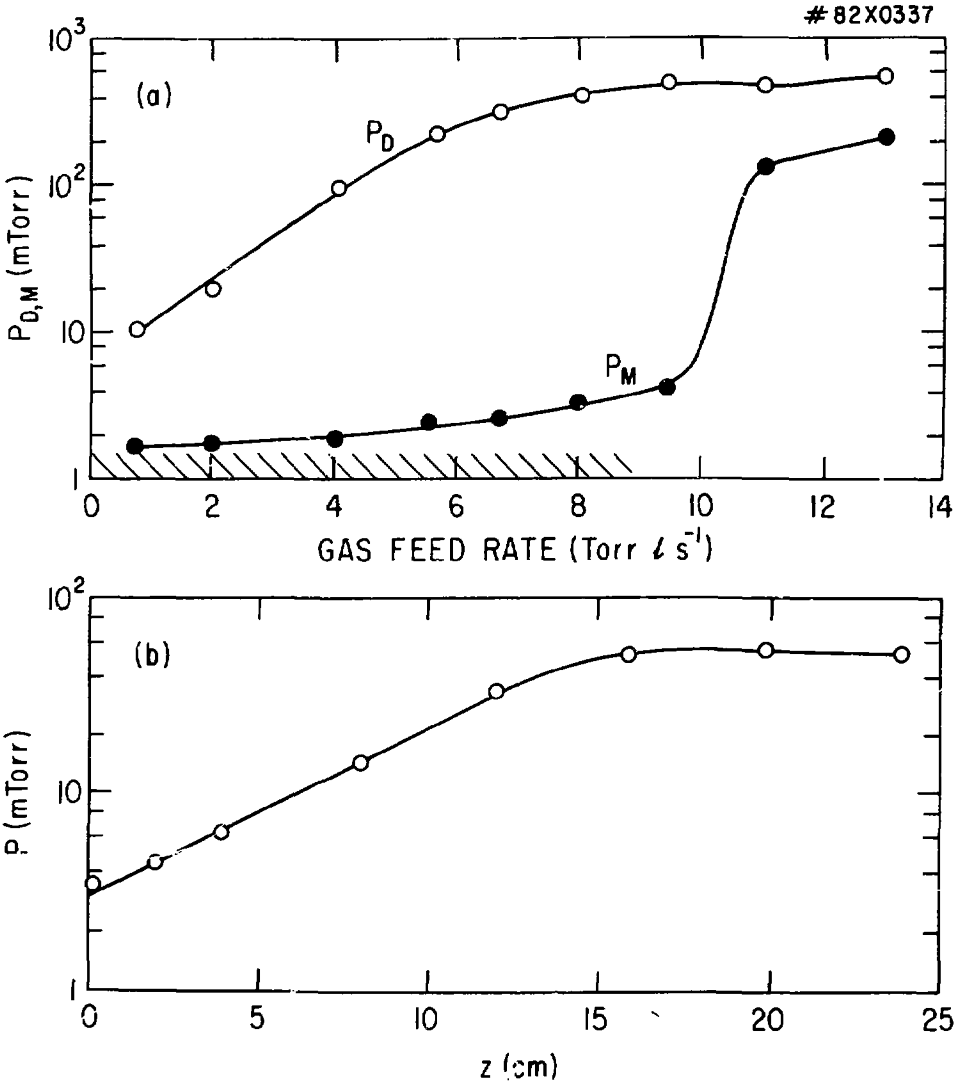


Fig. 3



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(a)
P_D
P_M
$P_{D,M}$ (mTorr)
10^3
10^2
10
1
0
2
4
6
8
10
12
14
GAS FEED RATE (Torr ℓ s^{-1})
(b)
P (mTorr)
10^2
10
1
0
5
10
15
20
25
z (cm)

Fig. 4