

## Experimental Simulation of the Gaseous Tokamak Divertor

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The first experimental simulation of the tokamak divertor using a gaseous collector is presented. Significant results are as follows: (i) neutral gas at a pressure of a few millitorr 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  $1 \sim 100$  MW; 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.<sup>1-3</sup> 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 as follows: (i) neutral gas at a pressure of a few millitorr ( $\ll n_e T_e$ ) 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 a divertor simulation device,<sup>4</sup> shown in Fig. 1. A short 200-A hydrogen arc provides a 1.2-cm-diam  $H^+$  plas-

ma which drifts along the magnetic field ( $\sim 2$  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 ( $\sim 5 \times 10^{13} \text{ cm}^{-3}$  and  $\sim 5$  eV) are typical of the cool plasma in the divertors of large tokamaks such as PDX (poloidal divertor experiment) 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.

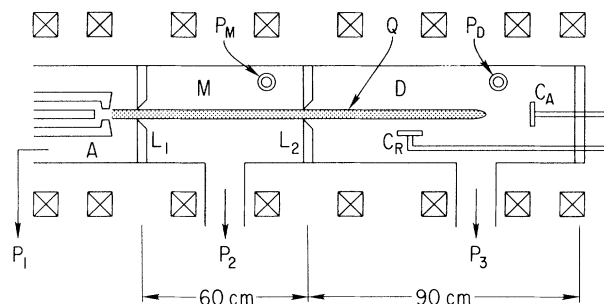


FIG. 1. Experimental arrangement configuration. A, arc-jet plasma source; Q, plasma column;  $L_{1,2}$ , limiters;  $C_{A,R}$ , calorimeters; M, main plasma chamber; D, divertor chamber;  $P_{M,L}$ , pressure gauges;  $P_{1,2,3}$ , pumps.

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 2 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  $M$

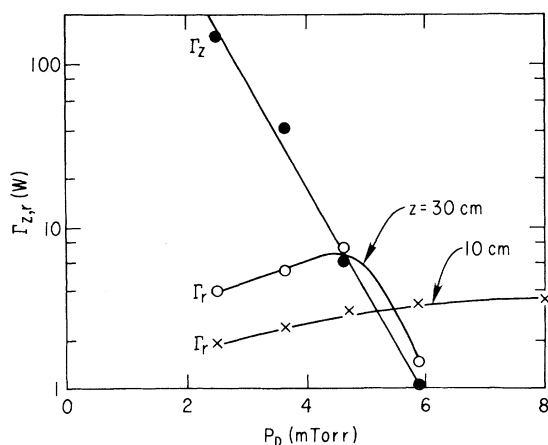


FIG. 2. Energy-collection rates vs gas pressure:  $\Gamma_z$ , axial collection by  $C_A$  at  $z = 70$  cm;  $\Gamma_r$ , radial collection by  $C_R$  at  $z = 30$  and 10 cm.

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<sup>5</sup> 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  $m_1 m_2 / (m_1 + m_2)^2$  in energy transfer counts against argon in the case of elastic collision. 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  $\Omega_i / \nu_{in}$ , where  $\Omega_i$  is the ion gyrofrequency and  $\nu_{in}$  the ion-neutral collision frequency. The axial decay length  $l$  of the plasma pressure  $P(z) = n_e(z) T_e(z)$  is plotted against  $(a/2.405) \Omega_i / \nu_{in}$ , for  $a = 1.2$  cm, in Fig. 3. These data are compared

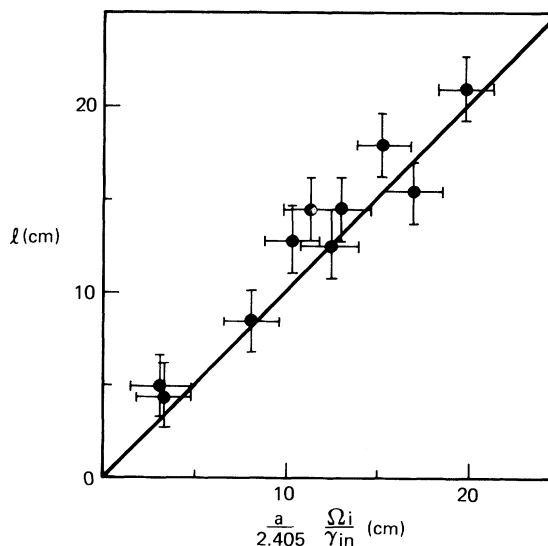


FIG. 3. Plasma pressure decay length (along  $z$ ) vs  $(a/2.405) \Omega_i / \nu_{in}$ . Solid line corresponds to the theoretical curve for  $a = 1.2$  cm.

with a simple fluid model containing ion-neutral collisions.

The relevant continuity and one-fluid momentum equations are

$$\frac{\partial(nv)}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{D_{\perp}}{T_e + T_i} r \frac{\partial P}{\partial r} \right), \quad (1)$$

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

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:

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

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<sup>6</sup>; the electron fluid is in good contact with both ends at the pressures ( $< 10$  mTorr) corresponding to Fig. 3. With  $\nu_{in}/\Omega_i \ll 1$  (as in the present experiment), and the boundary condition  $P = 0$  at  $r = a$  and  $P \rightarrow 0$  as  $z \rightarrow \infty$ , the above equations lead to a solution for the pressure,

$$P = P_0 J_0(r/a) e^{-z/l}, \quad (4)$$

where  $a$  is the plasma radius,  $J_0$  is the zeroth-order Bessel function, and  $l$  is the axial decay length given by the expression

$$l = (a/2.405) \Omega_i / \nu_{in}. \quad (5)$$

Estimating  $\nu_{in}$  from values of  $\langle \sigma v \rangle_{in}^5$  (which is relatively constant at low  $T_i$ ), we find that Eq. (5), corresponding to the straight line in Fig. 3, fits the data relatively well. Radial profiles  $P(r)$  show good agreement with the  $J_0(r/a)$  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.<sup>7-9</sup> Attaching a cylindrical metal tube (diameter 2 cm, length 7.5 cm) to the left-hand face of limiter  $L_2$ , to stimulate 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 mTorr ( $\lesssim n_e T_e$ , 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

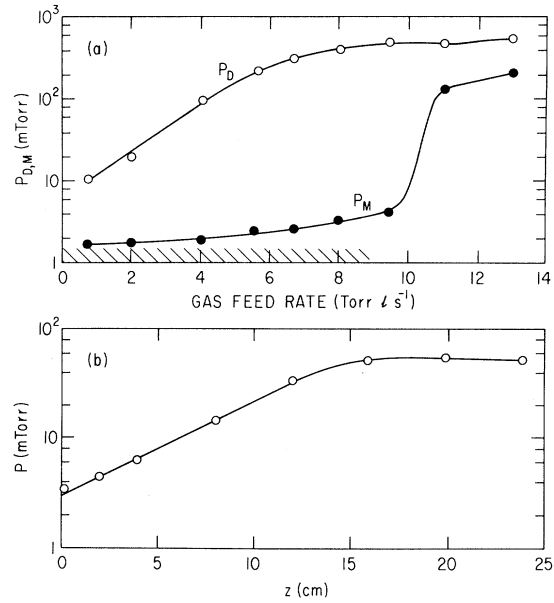


FIG. 4. (a) Gas pressure in divertor,  $P_D$ , and in main chamber,  $P_M$ , vs hydrogen-gas feed rate, showing feed rate range (hatched) for plugging of short connecting channel by plasma. (b) Gas pressure in long connecting channel vs axial distance.

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  $z \approx 13$  cm. The exponential pressure decay lengths of the three species of molecule are found to be in the ratio  $l_{\text{He}}:l_{\text{H}_2}:l_{\text{Ar}} \approx 1.4:1.0:0.7$ . These are ordered in the same way (as expected for momentum transfer) as the respective reciprocal rate coefficients,  $\langle \sigma v \rangle^{-1}$ , for elastic collisions with  $\text{H}^+$  ions, namely 2:1:0.7.<sup>10</sup> 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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## Electron Heating Due to Resonance Absorption of Moderate-Intensity Microwaves

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Measurements are presented of electron heating due to the resonance absorption of moderate-intensity ( $v_0/v_e \lesssim 0.3$ ),  $p$ -polarized microwaves. The results agree very well with computer-simulation calculations and warm-wave-breaking theory. The experimental results are shown to scale to laser parameters.

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The possibility of using lasers to compress and heat a pellet to thermonuclear conditions is under intense investigation. There is strong evidence that resonance absorption<sup>1,2</sup> is an important absorption mechanism for short-pulse, moderate-<sup>3,4</sup> to high-intensity<sup>5</sup> laser light.

We present here the first detailed measurements of electron heating due to the resonance absorption of moderate-intensity microwaves in a well-defined experiment [ $v_0/v_e \lesssim 0.3$ , or  $f\lambda^2/T_e^{3/2} \lesssim 10^{15}$  (W/cm<sup>2</sup>)  $\mu\text{m}^2/\text{keV}^{3/2}$ , where  $v_0 = eE_0/m\omega_0$ ,  $E_0$  is the peak electric field of the incident microwaves,  $\omega_0$  is the microwave frequency,  $v_e = (kT_e/m)^{1/2}$ ,  $f$  is the fractional microwave absorption,  $I$  is the intensity of the incident microwaves, and  $\lambda$  is the wavelength of the microwaves]. We measured the spatially and temporal-

ly resolved electron energy distribution function near the critical surface. We find that the energy distribution of the heated electrons changes on the ion time scale as the density profile is modified by the ponderomotive force. The heated electrons reach steady state when the asymptotic shelf-step density profile is formed. The heated electrons have a bi-Maxwellian energy distribution. The thermal electrons are not strongly heated ( $T_e \lesssim 2T_{e0}$ , where  $T_{e0}$  is the initial electron temperature), but the suprathermal (hot) electrons are very strongly heated ( $T_h/T_e \lesssim 11$  and  $n_h/n_c \lesssim 0.13$ ). These results are in very good ( $\pm 20\%$ ) agreement with electromagnetic computer simulations<sup>3,5</sup> of resonance absorption for laser parameters if the independent variable<sup>6</sup>  $fI\lambda^2/T_e^{3/2}$  is used. Our results also agree very well ( $\pm 20\%$ )