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Measurements of plasma flows in a divertor simulation *

F. Zonca [1], S.A. Cohen [1], J. Cuthbertson [1], J. Timberlake [1] and D. Ruzic [2]

[1] *Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA*

[2] *University of Illinois at Urbana-Champaign, IL 61801, USA*

The importance of plasma momentum fluxes in fusion reactor divertor operation is noted. Direct measurements have been made of the momentum flux from magnetized He, Ne, Ar and Kr plasmas onto solid carbon targets oriented normal to the magnetic field, as the target bias was varied between −50 and +40 volts. The inferred ion energies are compared with fluid sheath theory. Corrections due to kinetic effects and charge exchange are considered.

1. Introduction

Present concepts for the ITER divertor design employ solid armor tiles made of such materials as C, Be or W [1]. These are subject to high power fluxes [2] and intense erosion [3] by both steady-state and transient plasma heat loads. Plasma disruptions also may produce runaway electrons of sufficient energy [4] to penetrate through the divertor armor to the water-cooling channels.

One proposed solution is to use divertors whose neutralizer surfaces are made of liquid metals in the form of flowing films [5], droplet streams [6,7] or swirling baths. Eroded material is thus readily replaced, heat is distributed over larger surface areas, and water-cooling channels are removed from the locations of runaway electron impact. Technical questions remain, with especially important ones on corrosivity and tritium inventory. Among plasma-related issues are fluid instabilities of the liquid metals and enhanced erosion due to sheath potentials determined by nonlocal T_e values.

Fluid instabilities might be expected to arise from a "plasma wind", i.e., momentum transfer from the plasma to the liquid metal's surface. For a fixed power flow per unit area, the momentum flux increases as $T_e^{-1/2}$, and hence is large for high recycling divertors which have high plasma density and low temperature. Two-dimensional numerical simulations of plasmas in the ITER divertor region [2] show that the momentum flux can be expected to reach the equivalent of a ~ 100 km/h wind in air. At this value, the potential is clear for a plasma wind to deflect a droplet stream, to thin a flowing film, or to generate spray from a swirling bath. Each of these instabilities would compromise divertor operation. Whether or not a liquid metal divertor is used, small particulates are likely to approach the edge of tokamak plasmas. The momentum flux onto them could determine whether they will enter the plasma or be deflected away.

The sheath and presheath act as transducers that convert electron energy to ion momentum. Exact predictions for the momentum transfer across the plasma boundary onto solid surfaces require a kinetic, and possibly a Lorentz, code to model the angle of ion impact. This is particularly important when magnetized plasmas flow onto surfaces inclined to $\boldsymbol{B}$. Calculations by Chodura [8] show that ion impact angle is strongly affected by the angle of inclination of the magnetic field to the surface. The net effect of this result is about a factor of 2 in surface-normal momentum transfer.

Fluid sheath theory states that the potential drop between the sheath and material surface is

$$\Delta\phi_s = (kT_{es}/2e)\ln[(2\pi m_e/m_i)(1 + T_{is}/T_{es})], \qquad (1)$$

where T_{es}, T_{is} are the electron, ion temperatures at the sheath and the other symbols have their usual meanings [9]. Furthermore, in the fluid approximation, tilting an electrically floating surface in a magnetized plasma hardly changes $\Delta\phi_s$ [10]. Preliminary experiments on sheath potential distributions in low-density plasmas support these results [11]. However, when power input

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to a plasma is some distance away from the boundary (material surface), a temperature gradient can develop towards the boundary. Then if the plasma is collisionless, energetic particles originating near the heat input may reach the material surface without thermalizing. Krasheninnikov has recently shown that this may lead to a three-fold increase in electric potential [12]. Such a change would alter the momentum flow and ion energy, as well as associated sputtering rates.

The goal of the experiments described here is to study these processes with emphasis on momentum transfer. The results we report are for a carbon target oriented normal to the flow of noble gas plasmas having densities of $\sim 10^{13-14}$ cm^{-3} and electron temperatures $\sim$ 3–10 eV. The collisionality of these plasmas, the ratio of Coulomb mean-free-path to system size, is in the range 0.1–1.0, about the same as for the ITER SOL.

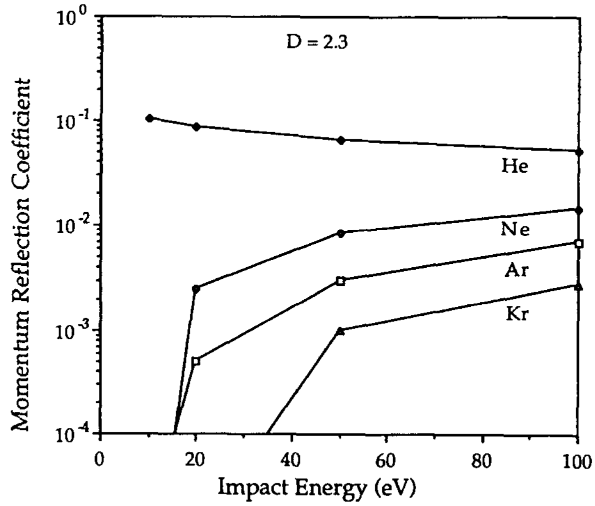

Fig. 1. Energy dependence of momentum reflection coefficient of ions impacting a carbon target at normal incidence, calculated using the Fractal TRIM code for a fractal dimensionality of 2.3. The processes included are backscattering and sputtering.

2. Experiment

Pulsed plasma beams, 2 cm in diameter, 12 cm long and up to 300 ms in duration, are produced from helium, neon, argon, and krypton feed gases in a magnetized (0.35 T) coaxial device which utilizes lower hybrid waves to sustain the plasma [13]. Densities up to 1×10^{14} cm^{-3} with electron temperatures in the range 3–10 eV, as determined from single Langmuir probes, are achieved [14]. The density is linearly proportional to μ-wave power for densities below that set by the short-wavelength criterion; the electron temperature varies little with power [13]. The ion temperatures are estimated to be < 1 eV [15]. In this parameter range, the plasma ions are expected to be singly ionized, which was confirmed spectroscopically for argon. The neutral gas density is $\sim 10^{14}$ cm^{-3}; thus the plasma is $\sim 50\%$ ionized. The density profiles are typically triangular while the electron temperature profiles are nearly flat.

The plasmas emerge from the coax and proceed 12 cm in a drift region before impacting a neutralizer plate made of carbon. The electrical bias of the plate is controllable in the range +40 to −50 volts. At more positive voltages the plasma is quenched by electron losses; at more negative voltages arcs may occur. Until the plasma quenches, its density is relatively independent of target bias.

The current density onto the target depends on its electric bias in a manner similar to a Langmuir probe characteristic. That is, for target bias voltages in the range $V_b < \phi_p$, the current density to the target is given by

$$J_T = j_+ - j_- \exp\left[-e(\phi_p - V_b)/kT_e\right], \qquad (2)$$

where $j_+ = en_i[k(T_e + 3T_i)/m_i]^{0.5}$, $j_- = 0.25en_e(8kT_e/\pi m_e)]^{0.5}$, and ϕ_p is the plasma potential, measured to be ~ 20 V.

The momentum flux from the plasma onto the neutralizer plate is measured by a plasma momentum meter (PMM) [15] which has a sensitivity of $10^{-1} \to 10^{2}$ dynes ($10^{-4} \to 10^{-1}$ g). The PMM response time is typically 25 ms for an impulsive load. From the time the plasma is initiated, it takes about 75 ms for the electric current to the carbon target to reach steady state. All pressure (force) measurements are taken in the time interval 150–250 ms after initiation, well into steady state.

Carbon was chosen as the target material for three reasons: to simulate the ITER choice of materials for the physics phase; for its refractory properties; and because of its low probability for reflecting impacting ions. This latter property was determined using the Fractal Trim code [16]. Results for energy- and species-dependent momentum reflection coefficients are shown in fig. 1 for normal incidence. The more massive noble gas ions have momentum reflection coefficients (reflected momentum/incident momentum) of $\lesssim 0.01$, which decrease with decreasing energy of impact, E_i. In these calculations the dimensionality of the surface was

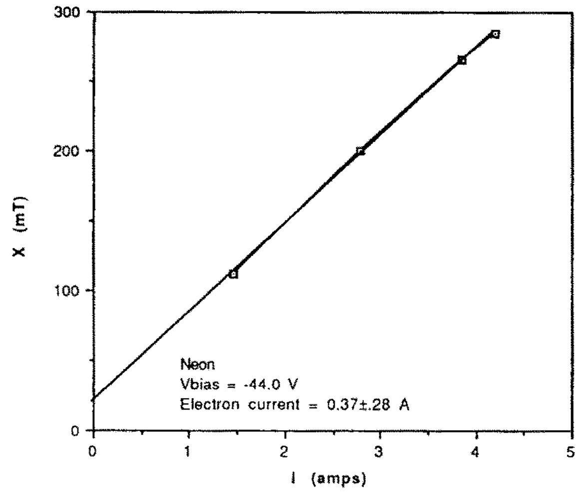

Fig. 2. Force (in mTorr) measured by the plasma momentum meter, as a function of current to the target, for a neon plasma and a fixed target bias of −44 V.

$d = 2.3$, i.e., atomically rough [16]. For a smoother surface, $d = 2.05$, the calculated momentum reflection coefficient of the massive noble gases shows a slight increase at $E_i \sim 40$ eV due to ejection of sputtered atoms.

3. Results and discussion

From kinematics, the force transmitted by the impacting plasma is given by

$$F_x = \{2m_i W_{ix}\}^{0.5} \alpha I_{+T}/e, \quad (3)$$

where α is the usual elasticity factor (~ 1.0 from fig. 1), I_{+T} is the ion current to the target, m_i is the ion mass, and W_{ix} the ion energy. The electron contribution to the force is negligible; and for the moment we ignore the contribution of neutrals to the force. For a fixed negative target bias, −44 V, the density of neon plasmas was varied at fixed electron temperature by varying the μ-wave power. The measured force has a reproducibility of ±2%. As shown in fig. 2, the force (shown in units of mTorr) is linear with total current. From the extrapolated nonzero intercept of the total current to the target at zero force, the contribution of electron

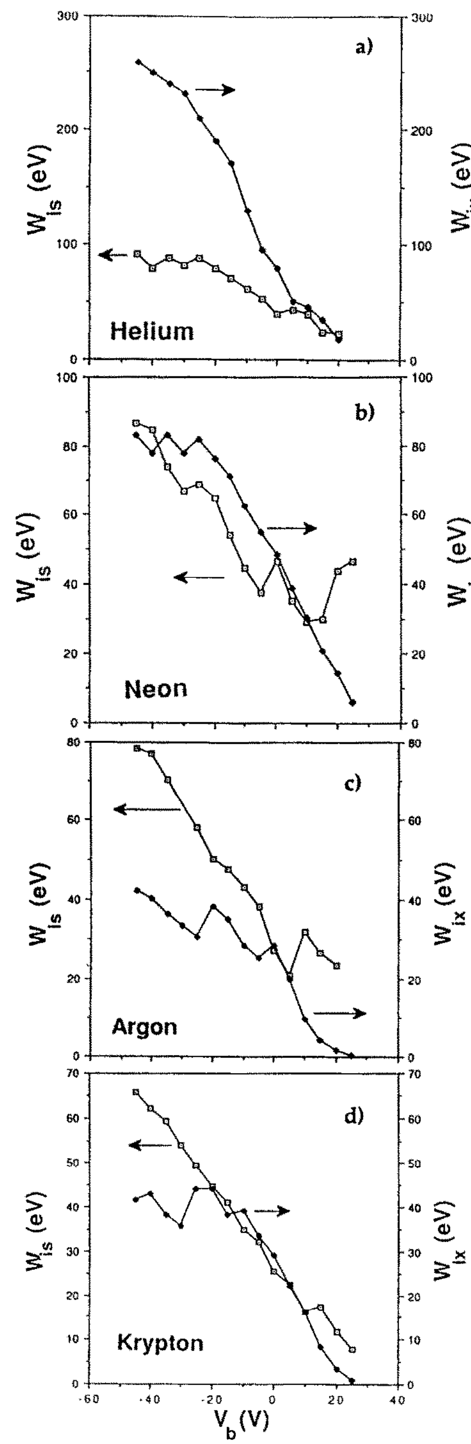

Fig. 3. Energy of He, Ne, Ar and Kr ions as they impact the target plate versus target bias, as inferred from eq. (3) for W_{ix} and eq. (4) for W_{is}.

current can be estimated to be 0.37 ± 0.28 A. Previously we have shown that the momentum flux for each noble gas plasma decreases smoothly towards zero as the target bias is increased [15].

By inverting eq. (3), the ion energy may be extracted, once the area of the plasma beam is measured and corrections to the total target current due to the electron contribution (at positive target bias) are made. These values, denoted as W_{ix}, are plotted in figs. 3a–d, for He, Ne, Ar and Kr. The ion energies decrease towards zero as the bias voltage is increased.

These results may be compared with predictions based on fluid sheath theory. Here the ion energy is given by

$$W_{is} = 5kT_i/2 + \left(m_i c_s^2\right)/2 - e\left(V_b - \phi_p\right), \quad (4)$$

where $c_s^2 = (3T_i + T_e)/m_i$. Values of W_{is} are also shown in figs. 3a–d. For Ne and Kr there is ±20% agreement between W_{ix} and W_{is} for $V_b < 10$ V. For Ar and He the discrepancy is about a factor of 2–3 over most of the bias range.

We have considered several mechanisms to explain the differences between W_{ix} and W_{is}. One that appears highly plausible is that the electron temperature, measured with a Langmuir probe 2 cm from the target, is not equal to the electron temperature at the target. Moreover, the detailed electron distribution at the target may not be a Maxwellian, as assumed in the derivation of eq. (4). This would qualitatively explain $W_{ix} > W_{is}$ for helium, because these plasmas have the lowest collisionality ~ 0.3, hence hot electrons from the heat input region can increase the sheath potential above that predicted by eq. (1). Also qualitatively, this would explain why $W_{ix} < W_{is}$ for Ar and Kr, because the temperature at the sheath may be lower than where the temperature is measured. Quantitative tests of this theory require not only more detailed measurements of plasma parameters along the plasma column, but the development of multidimensional kinetic models of the plasma which include atomic physics effects.

It should be noted that the contribution of neutrals to the momentum flux can be appreciable. We have estimated this effect to be most important for helium because of the long ionization mean-free-path and short charge-exchange mean-free-path.

4. Summary

We have pointed out the importance of momentum fluxes in tokamak divertors. Measurements of momentum fluxes have been made for plasma with similar collisionalities as expected in reactor divertors. The inferred ion energies are compared with those predicted by sheath theory. Factor of ~ 2 differences are seen. Plausible explanations, based on kinetic effects and charge exchange have been proposed. Quantitative comparisons await tests against more detailed models.

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