PPPL-2232

PLASMA PARTICLE AND ENERGY REFLECTION AT A WALL WITH AN OBLIQUELY INCIDENT MAGNETIC FIELD

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PPPL--2232

DE85 017682

ABSTRACT

The particle and energy reflection coefficients are calculated for a plasma incident at a wall with an obliquely incident magnetic field. The salient result of these calculations is that the reflection coefficients can approach unity when the magnetic field is incident at grazing angles. This reflection of particles and energy will be an important process in determining the particle and energy balance in the edge plasma.

The properties of a magnetically confined plasma are determined by a complex interrelationship between the heating processes, particle and energy transport, and the characteristics of the edge plasma. In a tokamak, the edge plasma is defined by either a magnetic divertor or material limiter. Recently, it has been demonstrated that changes in the edge plasma can have a strong effect on the central plasma parameters as evidenced in the high confinement (H-mode) observed with a divertor (ASDEX,[1] D-III,[2] PDX[3]) during neutral beam heating. A similar increased confinement behavior during neutral beam injection has been observed with the PDX Scoop limiter.[4]

The limiter or divertor is usually thought of as an energy and particle removal device.[5] This paper adopts another viewpoint, the limiter being an energy and particle reflector. In particular, the reflection coefficients for particles and energy are calculated for a plasma incident at a wall with an oblique magnetic field. It is shown that the shape of the limiter can strongly affect these reflection coefficients with the possibility of near unity reflection at grazing angles. Since a large fraction of particles leaving the plasma hit the limiter, this reflection of particles will be an important process in the edge plasma. Recent results from the D-III tokamak[2] indicate that the energy confinement time in limiter discharges is closely related to edge particle transport. Determination of the processes responsible for obtaining improved confinement in auxiliary heated discharges will be important in obtaining the goal of reaching energy breakeven (Q=1) in present tokamaks such as TFTR and ignition in future machines.

Plasma ions and electrons diffuse from the plasma center to the edge where they flow along magnetic field lines into the wall. The original particle trajectory will be modified by gyromotion around the magnetic field lines and acceleration by the electric field formed by the plasma sheath at the plasma-wall boundary. Chodura[6] originally analyzed this problem in a self-consistent manner assuming a collisionless Maxwellian plasma flowing to a particle absorbing wall at the sound speed (Bohm condition)

$$c_s = [(\gamma_i T_i - \gamma_e T_e)/m_i]^{1/2} , \qquad (1)$$

where $\gamma_i = 5/3$, $\gamma_e = 1$. He showed that the wall potential was weakly dependent on the impact angle and the ratio of the ion to electron temperatures. Using his average potential of $\phi = -2.5\ T_e$ and $T_i = T_e$, the impact angle ϕ for ions and electrons was recalculated as a function of the magnetic field direction θ. Figure 1 shows the results for the average impact angle which are in agreement with Chodura.[6] Variation of the plasma potential ($-T_e$ to $-3\ T_e$), electron temperature (10-5000 eV) and magnetic field (0.5-5 T) showed no change in these results. The average energies for the ions and electrons at the wall are about $\sim 7\ T_e$ and $2\ T_e$ (assuming $T_i = T_e$) and show little dependence on θ. The ions acquire this energy at the expense of the electrons which are decelerated at the sheath so that equal fluxes of ions and electrons strike the wall.

The particle and energy reflection coefficients are dependent on the incident species, target material, and impact angle. For the purpose of this analysis, the plasma ions were assumed to be deuterons and the wall was chosen to be carbon which is representative of most present tokamak discharges with limiters. The results for other ions and wall materials exhibit similar reflection characteristics. There are limited experimental data[7] concerning the angular dependence of hydrogenic reflection coefficients at the energies of interest (10-1000 eV). The several theoretical models[8-10] which calculate reflection coefficients are in general agreement with each other and the experimental data. For the purpose of this paper, the results of the TRIM code[8] were utilized. The angular dependence of the electron reflection coefficient for carbon, R_P[11], has been measured only at keV energies.[12] Since the reflection coefficient at normal incidence exhibits little energy dependence below a few keV,[13] it was assumed that the higher energy angular measurements are valid at the energies of interest. Figure 2 shows these deuteron and electron reflection coefficients as functions of the impact angle and energy for a carbon surface. Reflected particles initially near normal incidence undergo multiple scattering events which result in a small reflection coefficient. As the impact angle becomes grazing, the reflection coefficient approaches unity exhibiting the importance of single scattering events. To a good approximation, the ion energy reflection coefficients R_E[14] can be expressed in an energy independent form depending only on the particle reflection coefficients R_P,[8,15] $R_E = 0.22 + 0.73\ R_P$.[16] The electron energy reflection coefficient is nearly constant, $R_E \sim 0.5$.[17] For both ions and electrons, the reflection is mainly diffuse at normal incidence and becomes specular at grazing incidence. Almost all the incident ions are reflected as neutrals ($f^+ < 0.02$).[18] In addition to the reflected electrons, there are also secondary electrons emitted by electron ($\delta \sim 0.5$-1.0)[19] and ion bombardment ($\delta \lesssim 0.1$).[20] These electrons will modify the plasma potential, but not the results of Fig. 1. These results assume a smooth surface, though there are theoretical predictions[21] and experimental indication[7] that the results should also be valid for surfaces with roughness up to about micron. An initially rough carbon limiter in a tokamak will probably be "conditioned" by plasma erosion and deposition until microscopically smooth.[22]

Figure 3 shows the fraction of deuterons reflected from a carbon wall as a function of the magnetic field inclination for several edge plasma temperatures.[23] The calculation of the effective electron reflection coefficients is complicated since the reflected and secondary electrons are influenced by the magnetic field which can lead to the possibility of multiple wall collisions. Figure 3 shows the calculated electron reflection coefficient (neglecting secondary electrons) as a function of θ.[23] For the magnetic field near normal incidence, the reflection coefficient is small (R_p ~ 0.35) and all the electrons are accelerated back to the plasma center. When the magnetic field is near grazing incidence, a large proportion of reflected electrons undergo further wall collisions, reducing the effective R_p. The important result of these calculations are that the reflection of ions is highly dependent on θ and can approach unity while the reflection of electrons is weakly dependent on θ and remains small. Since the incident deuterons are reflected as neutrals, the deuterons will return back to the plasma unaffected by the sheath electric field with an energy up to seven times the plasma temperature.

The reflection of particles and energy at the limiter or wall has several effects on the edge plasma. Due to the extreme complexity of the edge plasma and the necessity of utilization of large computer codes to elucidate its features, it is difficult to quantify these effects. Nevertheless, it is possible to use a simple physical model to try to understand the importance of the edge. The plasma can be divided into the main and edge plasma regions with the boundary being defined by the first magnetic flux surface which intercepts a material surface such as a limiter or neutralizer plate. The plasma density and temperature profiles will be determined by equations involving heating and particle sources, radiation, charge-exchange efflux and diffusion. The plasma will evolve according to these equations subject to the constraints imposed at the edge. For this analysis, we will be mainly concerned with auxiliary heated plasmas, where a significant fraction of the energy and particle losses occur at the edge. Energy and particles will flow orders of magnitude faster along magnetic field lines as opposed to across them, which elucidates the importance of a very narrow region at the boundary. The power flow into the edge region will be limited to the input heating power (neglecting charge exchange and radiation). This model would then prescribe that improved plasma parameters could be obtained by fueling within or near the first flux surfaces which intercept materials. This would increase the density along these field lines and the power would be used more efficiently to ionize and heat the hydrogen as opposed to being lost to material heating. Fueling further out in the edge is less efficient since the dominant transport would be back to a material surface. This simple model can qualitatively explain the results obtained with the PDX[3] divertor where improved confinement was obtained only after changing the divertor from an open to a closed geometry. This reduced the main chamber pressure, decreased power flow to the neutralizer plate, and the fueling occurred close to the boundary region.

The importance of the limiter shape can be understood using this model. The reflection of ions at the limiter is equivalent to fueling the plasma with fast atomic neutrals. These fast neutrals will penetrate into the main plasma and will fuel it deeper than slow molecules emitted from the limiter or introduced by edge gas puffing. The more efficient refueling of the plasma by reflected neutrals could lead to a better overall confinement similar to the observed improved plasma properties obtained with pellet injection[24] as compared to edge gas puffing. The reflection of energy is also equivalent to less energy removal at the edge. These effects can raise the boundary density and temperature which could lead to improvement in the central plasma. An ideal limiter would be one which removed no energy or particles at the boundary. This can partially be achieved by proper shaping of the limiter to take advantage of increased reflection at grazing magnetic field angles.

To quantify how the limiter shape can affect particle and energy balance in the edge plasma, we will calculate these effects for a standard PDX rail limiter and the PDX Scoop limiter. The PDX rail limiter had a triangular cross section so that the magnetic field lines intercept it at an angle of about 62° to the normal. The PDX Scoop limiter faces the plasma with a front surface convex to the plasma so that the magnetic field incidence angle varied between 90° and 72° to the normal. The particle reflection coefficients were calculated using the results from Fig. 3 assuming a typical 100 eV edge plasma temperature. The rail limiter plasma deuteron reflection coefficient was found to be about 31%, while the Scoop limiter exhibited a significantly larger reflection coefficient of 59%. The electron reflection and secondary emission coefficients are comparable for both limiters. It is more difficult to quantify the effect of limiter shape on the energy balance in the boundary plasma. One difference between the Scoop and rail limiters, is that the Scoop ion reflection coefficient is significantly larger so there will be equivalently less heat removed by the limiter. A more important effect will be that there will be a need for less molecular fueling (limiter emission or gas puffing) for Scoop discharges. This implies that only about 2/3 as much energy will be expended with the Scoop discharges to perform the several cycles of ionization and losses to the material surfaces necessary to fuel the main plasma. These results show that the difference in these two limiter shapes can greatly affect the particle and energy flow in the edge plasma. For typical PDX plasmas, the particle confinement time is about 30 msec, and the limiter is bombarded with ions at a rate of about $4 \times 10^{21} sec^{-1}$ while the plasma is refueled by gas puffing with molecules at a rate of $3 \times 10^{20} sec^{-1}$. The power incident on the limiter is about 10^6 W during neutral beam injection ($P_{inj} \sim 2\text{-}4 \times 10^6$ W). There are several experimental observations indicating that there was increased reflection and atomic fueling for the Scoop versus rail limiter discharges. Thomson scattering[25] observed higher (~50%) edge density and temperature implying improved particle and energy confinement at the boundary region. The gas flow required to maintain similar discharges[26] was significantly less (~ 5%) for the Scoop limiter discharges which could be explained by less particle loss due to limiter implantation. The D_α emission away from the limiter in Scoop discharges was only a fraction (~ 25%)[27] of the emission observed in rail discharges, which indicates less edge neutral density. The passively pumped plenum of the Scoop limiter was probably not responsible for the observed increased confinement since only a small fraction ($\lesssim$ 10%) of plasma particles incident on the limiter entered the plenum and after about 50 msec, particle equilibrium was established. It is believed that it is the difference in particle reflection due to the limiter shape that is responsible for the increased energy confinement observed in PDX discharges heated with neutral beams.

In summary, it has been shown that near unity reflection coefficients can be obtained for particles incident on a wall even when sheath and gyromotion effects are included. These large reflection coefficients can be obtained by designing limiters with surfaces such that the magnetic field intercepts the limiter at a grazing incidence. This effect could be responsible for the increased energy confinement observed with the PDX Scoop limiter. Further elucidation of this effect requires further laboratory measurements of the angular dependence of the reflection coefficients and careful experiments on auxiliary heated tokamaks with different limiter geometries.

ACKNOWLEDGMENT

This work is supported by the U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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FIGURE CAPTIONS

FIG. 1. Average particle impact angle ϕ as a function of the magnetic field direction θ for a plasma incident at a wall.

FIG. 2. Particle reflection coefficients for deuterons and electrons incident at a carbon surface as a function of the impact angle θ and the energy. The electron reflection coefficient exhibits little dependence on energy for E = 20-1500 eV.

FIG. 3. Deuterium and electron reflection coefficients for a Maxwellian plasma incident at a carbon surface as a function of the magnetic field direction θ. The electron reflection coefficient exhibits little dependence on energy temperature for T = 20-1500 eV.

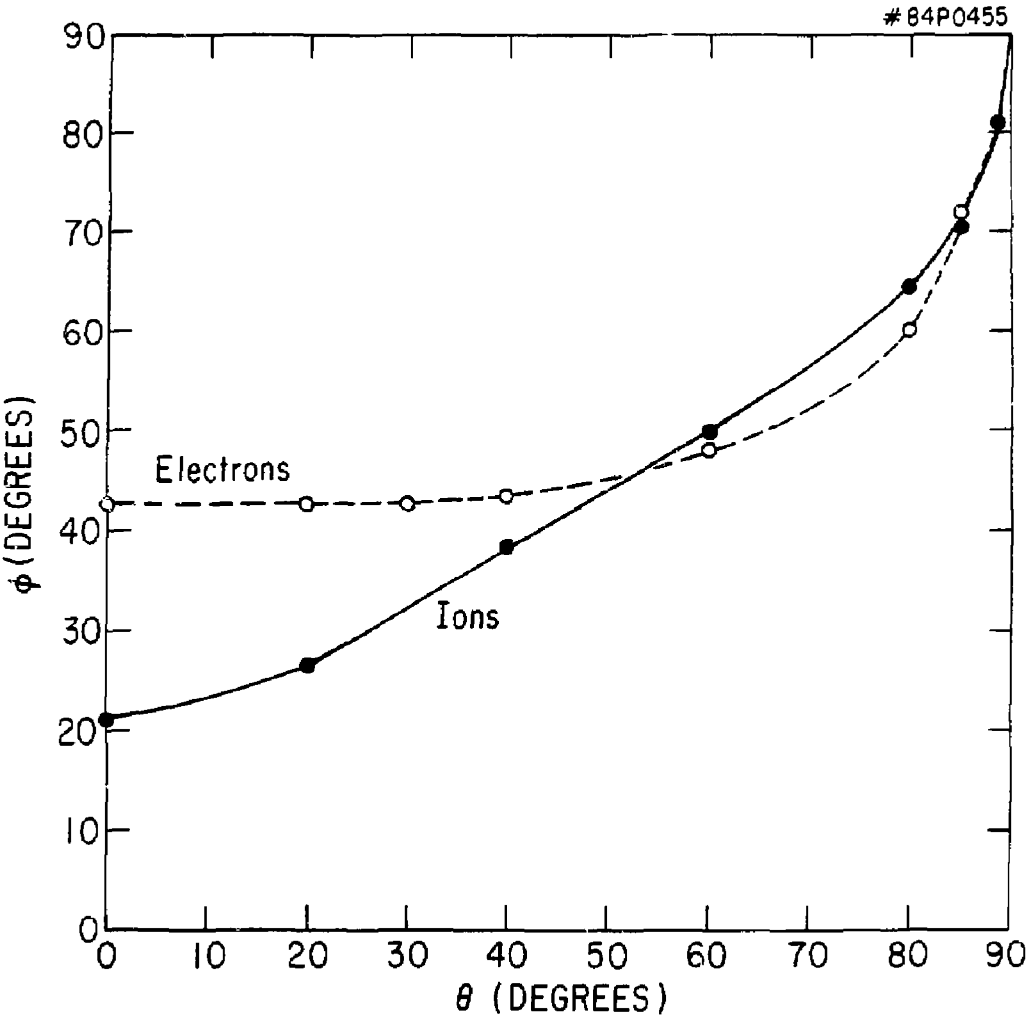
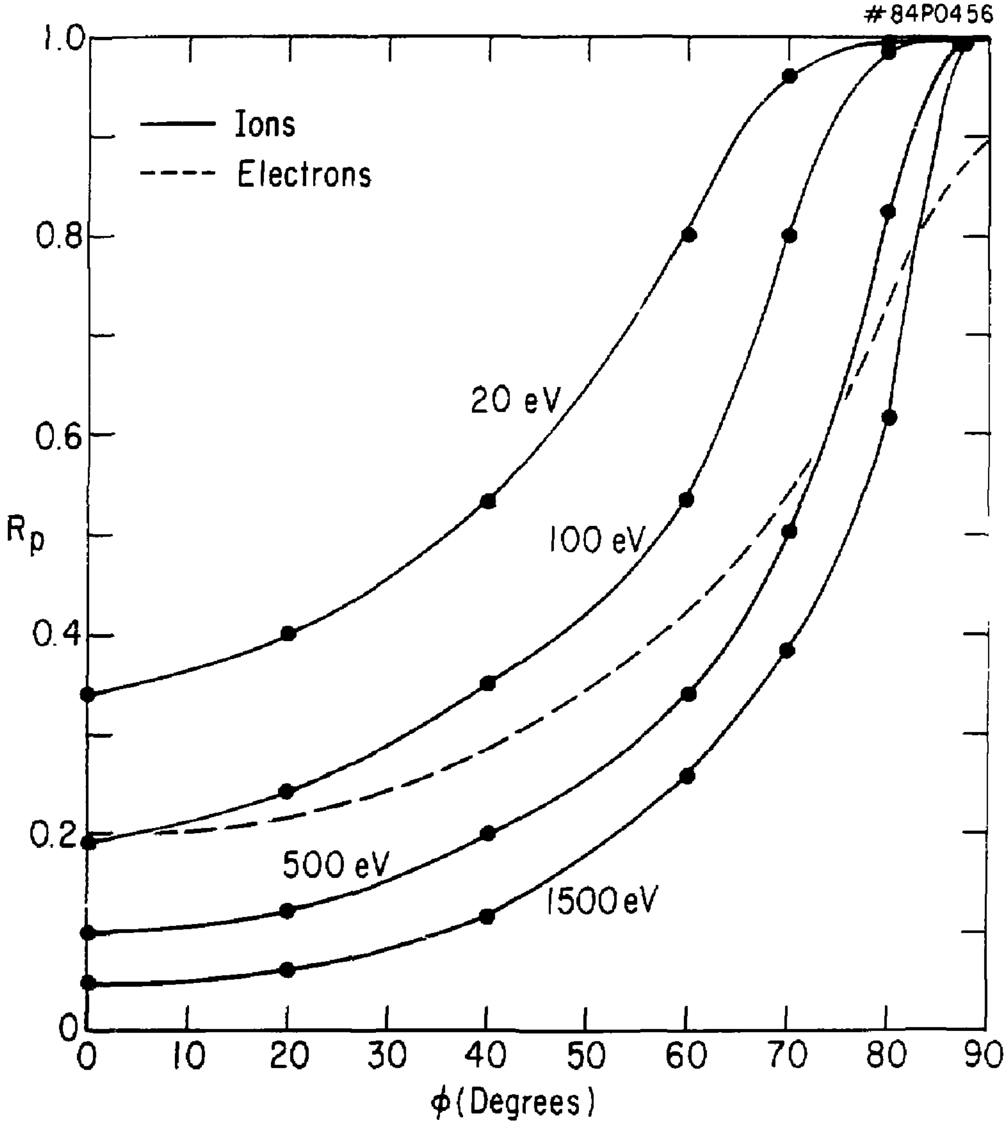

#84P0455
φ (DEGREES)
θ (DEGREES)
Electrons
Ions
0
10
20
30
40
50
60
70
80
90

Fig. 1



#84P0456
1.0
0.8
0.6
0.4
0.2
0
Ions
Electrons
20 eV
100 eV
500 eV
1500 eV
Rp
0
10
20
30
40
50
60
70
80
90
φ (Degrees)

Fig. 2

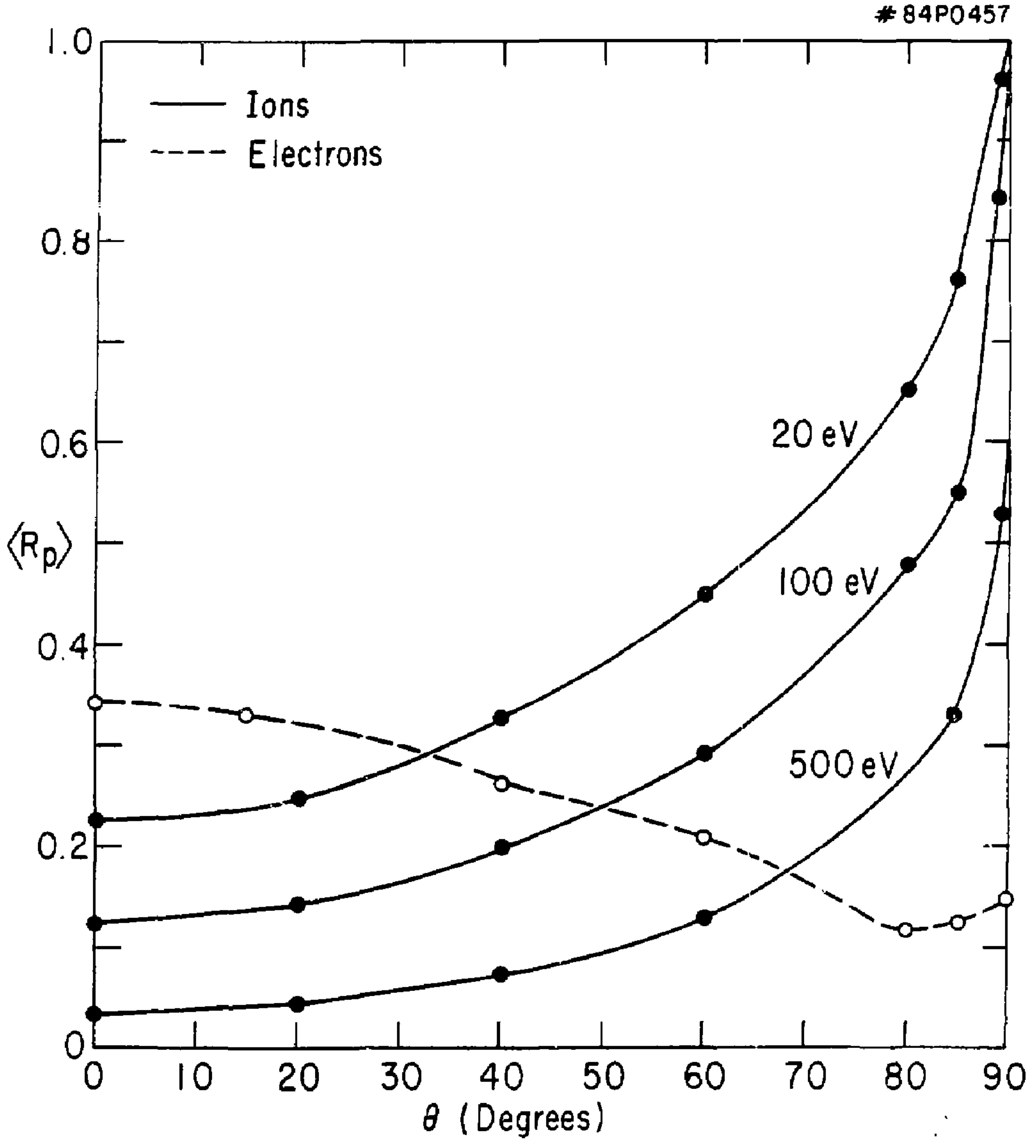

#84P0457
Ions
Electrons
1.0
0.8
0.6
0.4
0.2
0
⟨Rp⟩
20 eV
100 eV
500 eV
0
10
20
30
40
50
60
70
80
90
θ (Degrees)

Fig. 3

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