Distribution Categories:
Magnetic Fusion Energy (UC-20)
Plasma Systems (UC-20a)
Magnetic Systems (UC-20b)
Theoretical Plasma Physics (UC-20g)

ANL/FPP/TM-142

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

PLASMA SHEATH REGION NEAR A BOUNDARY
WITH POSITIVE ION BACKSCATTERING

by

Jeffrey N. Brooks

Fusion Power Program
and
Applied Physics Division

DISCLAIMER
This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

April 1981

jb
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
INTRODUCTION	2
EFFECT OF BACKSCATTER	7
SENSITIVITY TO BACKSCATTERED PROFILE	10
DISCUSSIONS	14
CONCLUSION	16
ACKNOWLEDGMENT	17
REFERENCES	17

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1	Model geometry	3
2	Backscattered intensity profile models	6
3	Normalized sheath potential and heat transmission factor as a function of ion and electron reflection from the boundary	8
4	Normalized sheath potential and heat transmission factor as a function of R_1 , for space-charge limited electron reemission .	9
5	Density, electric field, and potential, for $R_1 = 0.15$ and space-charge limited electron reemission	11
6	Density, electric field, and potential, for $R_1 = 0$ and space-charge limited electron reemission	12
7	Ion distribution function for $R_1 = 0.15$ and space-charge limited reemission	13
8	Self-sputtering coefficient of iron as a function of R_1 and electron edge temperature T_e	15

LIST OF TABLES

I	Sensitivity of Sheath Parameters to Backscattered	14
---	---	----

PLASMA SHEATH REGION NEAR A BOUNDARY
WITH POSITIVE ION BACKSCATTERING

by

Jeffrey N. Brooks

ABSTRACT

The sheath region at a boundary perpendicular to a magnetic field has been studied by numerically solving time-independent Vlasov-Poisson equations for a DT plasma. Boundary conditions are specified for particles entering the sheath region and for particles returning from the boundary. The effect of hydrogen ion backscatter as well as electron reemission has been examined. For a space-charge limited electron reemission condition, even a small amount of ion backscatter can change the sheath parameters substantially, lowering the sheath potential and increasing the heat transmission. This could be important in lowering the edge temperature, and the sputtering rate in future fusion devices.

INTRODUCTION

The sheath region near an electron reemitting boundary has been studied by various authors, e.g. Refs. 1-3. The sheath potential is found to be very sensitive to electron reemission, reaching a minimum normalized value of about one-half the electron-edge temperature for space-charge limited reemission. Even for this minimum value however, sputtering, particularly by highly stripped impurity ions, may be unacceptably high; see, for example, Ref. 4. However, in addition to electron reemission, there could be significant hydrogen backscatter from many fusion reactor materials [5,6]. Such backscatter could nullify some of the electron space charge in the sheath region and so permit a higher value of electron reemission. This subject has been studied with a plasma kinetic code which solves for the ion and electron distribution functions and the self-consistent electric field in the sheath region. This type of solution permits a detailed specification of the boundary conditions, e.g. the velocity structure of the backscattered ions, and also shows the behavior of the density, electric field, etc., in the sheath region. Based on this analysis it appears that plasma-edge conditions, and impurity content, could be quite dependent on the reemission and backscatter properties of the boundary.

Figure 1 shows the problem geometry. The boundary is perpendicular to a magnetic field so particles flow in the x-direction and are normally incident on the boundary. The point $x = a$ is, by definition, the start of the sheath region. The time-independent Vlasov-Poisson equations are solved for in the sheath region as follows:

$$v_x \frac{\partial f_1}{\partial x} + \frac{eE}{M_1} \frac{\partial f_1}{\partial v_x} = 0, \quad (1)$$

Fig. 1. Model geometry.

$$v_x \frac{\partial f_e}{\partial x} - \frac{eE}{M_e} \frac{\partial f_e}{\partial v_x} = 0, \quad (2)$$

$$\frac{dE}{dx} = \frac{e}{\epsilon_0} (N_i - N_e), \quad (3)$$

where $f_k = f_k(x, \vec{v})$ is the distribution function for the k -th species (i = ions, e = electrons), M_i and M_e are the masses; e is the proton charge, $E = E(x)$ is the electric field, and $\vec{v}$ is the (three-dimensional) velocity vector. An ion mass corresponding to 2.5 AMU is used. The densities in Eq. (3) are given by:

$$N_k(x) = \int_{-\infty}^{\infty} f_k d^3v . \quad (4)$$

Similarly the particle and heat fluxes are computed by the first and second moments, respectively:

$$\Gamma_k(x) = \int_{-\infty}^{\infty} v_x f_k d^3v , \quad (5)$$

$$q_k(x) = \frac{1}{2} M_k \int_{-\infty}^{\infty} v_x^2 f_k d^3v , \quad (6)$$

where numerical integration is used to obtain N , Γ , and q . The heat transmission capability of the sheath is defined by a factor γ such that:

$$q_i(0) + q_e(0) = \gamma K T_e (\Gamma_i + \Gamma_e) , \quad (7)$$

where T_e is the electron temperature at $x = a$. (Since the sheath region is too small to permit much ionization of neutrals, the particle fluxes are constant and can be evaluated anywhere in the sheath.)

The boundary conditions used are as follows: At $x = a$ the particles travelling toward the boundary are specified by half-Maxwellian distributions in the x -direction and by full Maxwellian distributions in the y - and z -directions. The distributions are characterized by a temperature T_K , ion drift velocity V_D , and a normalizing parameter C_K as follows:

$$f_i(a, \bar{v}) = C_i \left(\frac{M_i}{2\pi K T_i} \right)^{3/2} e^{-\left(M_i / 2 K T_i \right) \left[(v_x - v_D)^2 + v_y^2 + v_z^2 \right]}, \quad v_x \leq 0, \quad (8)$$

$$f_e(a, \bar{v}) = C_e \left(\frac{M_e}{2\pi K T_e} \right)^{3/2} e^{-\left(M_e / 2 K T_e \right) \left[v_x^2 + v_y^2 + v_z^2 \right]}, \quad v_x \leq 0.$$

Two additional parameters used in specifying the boundary conditions are:

$$\alpha = \frac{(1/2)M_i v_D^2 + (3/2)K T_i}{(3/2)K T_e} \quad \beta = T_i / T_e,$$

where α is, approximately, the ratio of the average ion to electron energy at the start of the sheath region. Values of $\alpha = 1$ and $\beta = 0.25$ have been used in this analysis.

At the boundary, distribution functions corresponding to ion and electron reemission are specified. Secondary electrons are represented by reemitting low energy (~ 1 eV) electrons with a coefficient R_e such that the flux of secondary electrons is equal to R_e times the electron flux to the boundary. By varying R_e the effect of ion-induced and thermally desorbed electrons is also included.

Data for treating positive ion reemission has come primarily from Refs. 5-6. This work shows up to $\sim 15\%$ positive ion backscatter from various targets and at various energies. There are some difficulties, however, in extrapolating these and other experimental results to future fusion devices. The incident particle energies used are, of necessity, higher than those expected in a fusion reactor. Present measurements are for free space conditions. Positive ion yields could be higher at lower incident energies (≤ 1 keV) due to an increase in elastic collisions. The form of the backscatter energy distribution could

Fig. 2. Backscattered intensity profile models.

also be different, in the presence of a plasma, and with simultaneous electron bombardment. To account for some of these uncertainties, we have modled the positive backscatter with several forms of energy distribution functions. These are shown in Fig. 2. Profile A was used as a reference for most of the calculations. This has a flat intensity with energy, up to an energy E_x which is defined as the average x-directed energy of ions hitting the boundary. The distribution function for this case is:

$$f_i(0, v_x) = \begin{cases} \frac{R_i \Gamma_i^-}{v_x \bar{v}_x}, & 0 \leq v_x \leq \bar{v}_x \\ 0, & v_x > \bar{v}_x, \end{cases} \quad (9)$$

where R_i is defined as the ion-reflection coefficient, $\bar{v}_x$ is the velocity corresponding to $\bar{E}_x$, and $\Gamma_i^- = \int_{-\infty}^0 v_x f_i d^3v$ is the ion flux impinging on the boundary.

(For numerical reasons, backscattered ions were not specified for energies less than 1 eV).

Finally, the remaining boundary conditions are that at $x = a$, the ion and electron densities and fluxes must be equal:

$$N_i(a) = N_e(a)$$

$$\Gamma_i(a) = \Gamma_e(a) .$$

Equations (1)-(3) are solved numerically by a midpoint-centered finite difference code. An iterative procedure is used where the parameters a , C_i , and C_e are varied in order to satisfy the boundary conditions. Therefore, at convergence, the code solves for the width of the sheath region, as well as the distribution functions and electric field.

EFFECT OF BACKSCATTER

Figure 3 shows the behavior of the sheath potential and the heat transmission factor for the case of no ion backscatter and for 15% backscatter. Both curves terminate at their respective space-charge limits in R_e . For a fixed value of R_e , the ion backscatter is seen to bring about a small increase in sheath potential. This is due to the decrease in the net ion flux hitting the boundary, which then requires a correspondingly higher potential to reduce the electron flux. More significantly, the ion backscatter extends the space-charge limit so that ϕ is lowered and γ raised, compared to the $R_i = 0$ case. This is important because for many materials and plasma-edge temperatures, the sheath is likely to be at the space-charge limit. For example, for iron, the secondary electron emission coefficient is greater than unity for a range of electron energies of about 100 to 1000 eV [7] and this is a likely range of

Fig. 3. Normalized sheath potential and heat transmission factor as a function of ion and electron reflection from the boundary.

edge temperatures in many fusion reactor designs. This is also true for several low-Z coating materials.

Figure 4 focuses on the space-charge limit case, where the sheath parameters ϕ and γ are shown as a function of R_i and where for each R_i the sheath is at the space-charge limit. As shown, γ increases linearly with R_i , due to the increase in the hot electron flux to the boundary. In contrast, the sheath potential decreases substantially at first, and then saturates at a value of about $e\phi/KT_e = 0.16$. The reason for this saturation is that the sheath potential

Fig. 4. Normalized sheath potential and heat transmission factor as a function of R_i , for space-charge limited electron reemission.

serves to turn around some of the reemitted ions and so affects the ion flux to the boundary as well as the electron flux. At high values of R_i the sheath acts as much to retard backscattered ions from reaching the plasma as it does to retard electrons from the plasma from reaching the boundary. (This saturation effect, as well as the linear behavior of γ was verified out to a value of $R_i = 0.5$, although this was not plotted in Fig. 4.)

Figure 5 shows details of the sheath region, for the typical case of $R_i = 0.15$ and R_e at the space-charge limit. Figure 6 shows the case for $R_i = 0$ for comparison. In these graphs, distance is normalized to an electron debye length evaluated at $x = a$. (The ion and electron densities are normalized to their values at the start of the sheath region, and the electric field and the potential are normalized to their maximum values. In both cases the electric field is zero at the boundary and peaks within one debye length. For $R_i = 0.15$, the ion density, instead of falling monotonically, peaks near the boundary. This is due to the ion backscatter, and serves to nullify some of the electron space charge. Also, for $R_i = 0.15$, the width of the sheath region is reduced from about 14 to 5 debye lengths.

Figure 7 shows the ion distribution function for the $R_i = 0.15$ case, at $x = 0$ and $x = a$. If there were no backscatter, f_i would always be zero for $V_x > 0$. (As mentioned previously, f_i is not specified for energies < 1 eV.) Backscattered ions having less energy than the sheath potential are turned around in the sheath region and return to the boundary. Hence f_i is reduced in going from $x = 0$ to $x = a$. These turned-around ions show up at the boundary for $V_x < 0$ as shown. The turned-around ions can also contribute to extra sputtering; this is not significant for $R_i = 0.15$ but would be significant if the backscatter were appreciably higher.

SENSITIVITY TO BACKSCATTERED PROFILE

The effect of the backscattered intensity profile on the sheath parameters was examined using profiles B and C of Fig. 2, for space-charge limited electron reemission. Profile B represents more backscattering at lower energy than the reference profile A while profile C represents more high-energy backscattering. Table I summarizes the differences among these profiles for

Fig. 5. Density, electric field, and potential, for $R_1 = 0.15$ and space-charge limited electron reemission.

Fig. 6. Density, electric field, and potential, for $R_i = 0$ and space-charge limited electron reemission.

Fig. 7. Ion distribution function for $R_i = 0.15$ and space-charge limited reemission.

TABLE I. SENSITIVITY OF SHEATH PARAMETERS TO BACKSCATTERED INTENSITY PROFILE ($R_i = 0.15$ AND FOR SPACE-CHARGE LIMITED ELECTRON REEMISSION)

Profile	$e\phi/KT_e$	γ
A	0.18	18.5
B	0.43	16.4
C	0.16	17.8

$R_i = 0.15$. The value of γ is fairly insensitive to the profile. The sheath potential is more sensitive, being lower for profile C and higher for profile B. In general, the behavior of ϕ for different values of R_i is similar to Fig. 4 except that ϕ saturates earlier for profile C and later for profile B.

Also examined was the effect of high energy electron emission. Such electrons could arise from (1) elastic scattering of energetic electrons; and (2) photo-emission of electrons. These were simulated in the code by allowing 5% of the returning electrons from the boundary to have an energy equal to the average energy of the impinging electrons. This had no substantial effect; the space-charge limit on the low energy electrons is merely reduced by about 5% and the sheath parameters remain about the same. Therefore, small amounts of high energy electrons will not change the sheath parameters. Likewise, small amounts of backscattered H^- ions will not significantly affect the sheath.

DISCUSSIONS

The sheath region in a fusion device will be important in two related respects: (1) in affecting sputtering; and (2) in affecting the plasma-edge temperatures. An example of the possible effect of ion backscatter on sputtering, a calculation was made for iron self-sputtering as a function of R_i for

Fig. 8. Self-sputtering coefficient of iron as a function of R_i and electron edge temperature T_e .

space-charge limited electron reemission. This is shown in Fig. 8. For each of the two edge temperatures used, the sputtering coefficient was computed using the formula of Ref. 8. This gives for iron:

$$S_{Fe \rightarrow Fe} = 2.1 \times 10^6 \frac{(E - 4.3)}{(E + 3.4 \times 10^4)^2},$$

where E is the energy, in eV, of the impinging Fe ions and is taken to be the edge electron energy plus the energy acquired in the sheath:

$$E = \frac{3}{2} K T_e + e \bar{Z} \phi ,$$

where $\bar{Z}$ is the average charge state ($\bar{Z} \approx 15$ for $T_e = 200$ eV and $\bar{Z} \approx 10$ for 100 eV), and ϕ is the sheath potential from Fig. 4. As shown at a given edge temperature, a 15% ion backscatter can reduce self-sputtering by about 50%. Also, a lower-edge temperature is easier to obtain since more heat will be conducted through the sheath region for nonzero R_1 . Fundamentally, however, comparatively low edge temperatures will still be needed to obtain an acceptable self-sputtering coefficient ($S \lesssim 1$) for iron and higher-Z materials, although the presence of ion backscatter will increase the acceptable temperature range.

For low-Z coatings, ion backscatter could help or hurt depending on the material, and the plasma-edge conditions. For a pure beryllium coating, backscatter may not matter since the secondary electron reemission is low [7]. For other coatings, and/or oxide contaminated surfaces, secondary electron emission may be high. Here backscatter would lower the energy of both ions and charge-exchange neutrals hitting the various plasma boundaries. Since sputtering yields for low-Z materials peak at intermediate energies, this could increase sputtering if the energies would have been above the peak, in the absence of ion backscatter. Conversely, sputtering would decrease if the energies were already lower than the peak.

CONCLUSION

The effect of ion and electron reflection from a boundary on the plasma sheath region was computed using a kinetic model. Small amounts of ion backscatter was found to significantly change the sheath parameters, if electron reemission is high. In general, the sheath potential is lowered and the heat

transmission coefficient is increased. The sheath width is also affected, being reduced by about a factor of 3 in going from zero ion backscatter to 15% backscatter. Changes in the sheath parameters in a fusion reactor boundary can significantly change the edge temperature and sputtering rate. This suggests the need for more understanding of the plasma-surface interaction properties of the fusion boundary materials.

ACKNOWLEDGMENT

I would like to acknowledge the helpful discussions with Manfred S. Kaminsky and Dale L. Smith regarding this work.

REFERENCES

- [1] HOBBS, G. D., WESSON, Plasma Phys. 9 (1967) 85.
- [2] FUCHS, G., NICOLAI, J. Nucl. Mater. 76 & 77 (1978) 573.
- [3] HARBOUR, P. F., HARRISON, M. F. A., J. Nucl. Mater. 76 & 77 (1978) 513.
- [4] BROOKS, J. N., J. Nucl. Mater. 93 & 94 (1980) 437.
- [5] ECKSTEIN, W., VERBEEK, H., Max-Planck-Institute fur Plasmaphysik Report IPP 9/32 (1979).
- [6] BHATTACHARYA, R. S., ECKSTEIN, W., VERBEEK, H., Surface Science 93 (1980) 563.
- [7] WHETEN, N. R., Methods of Experimental Chemistry (Academic Press, 1963).
- [8] SMITH, D. L., J. Nucl. Mater. 75 (1978) 20.