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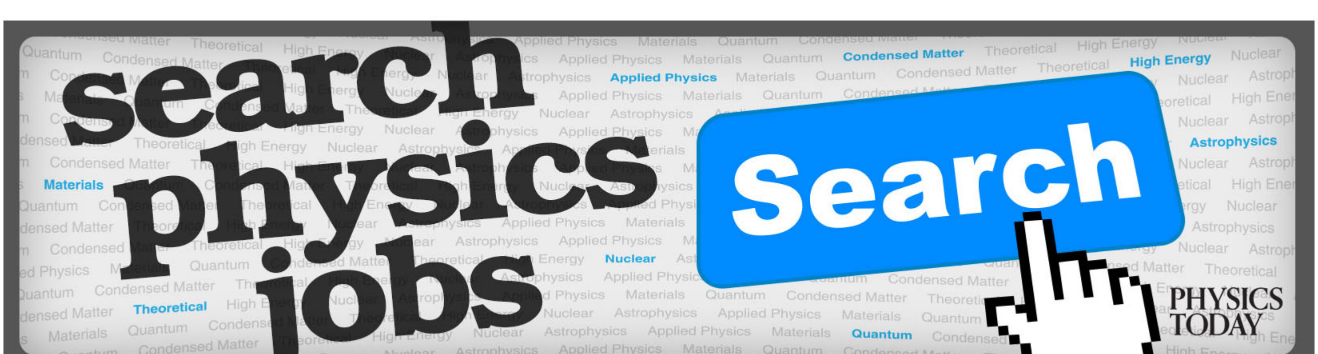

Application of the results of carbon pellet modeling to the problem of plasma penetration

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The assumptions of the evaporation model for low-Z pellets interacting with magnetic fusion plasmas developed by Parks are tested. These assumptions are that the vapor density profile in the region adjacent to the pellet surface falls off with radial distance as $r^{-\alpha}$, where $5<\alpha<6$, and that the ionization time for the transition between charge states τ_{zi} is much less than a flow time for the vapor in this same region τ_f (i.e., for $r<\sim 3$ sonic radii). The first assumption is tested by solving a two-parameter eigenvalue problem for the evaporation cloud in the region interior to the sonic radius; the results are found to be consistent with the low-Z evaporation model. The second assumption, that $\tau_{zi} \ll \tau_f$, is tested at the sonic radius using the results from atomic physics and the low-Z evaporation model. It is found that indeed $\tau_{zi} \ll \tau_f$ for plasmas with parameters close to thermonuclear conditions (e.g., CIT), but not for those of smaller Tokamaks such as TEXT. The results of pellet penetration calculations for the conditions of the carbon-pellet injection experiments into TEXT and low-density TFTR plasmas are presented that show better agreement with experiment if the shielding fraction is calculated at each step of the pellet-penetration calculation, the effect of ionization is ignored, and if the effect of possible uncertainties in the background plasma parameters is included.

I. INTRODUCTION

The modeling of the interaction of low-Z pellets with magnetic fusion plasmas is important for several reasons due to their potential use in plasma refueling,[1] current density diagnostics,[2] and alpha-particle diagnostics.[3] An important model for the interaction of plasmas with low-Z pellets was developed by Parks[4] based on the vapor shielding phenomenon. Although this model has been fairly successful in predicting the penetration of carbon pellets into Alcator and T-10,[4] there are some discrepancies with similar experiments on the TEXT device, namely that the model overestimates the range of pellets in the TEXT plasmas.[5,6] This discrepancy has been believed to be the result of a nonthermal electron distribution in that device causing a higher evaporation rate than that predicted by the model which is based on the assumption of a Maxwellian electron distribution.

In the work reported here, several assumptions in the low-Z model were tested by solving the steady-state flow problem self-consistently by means of a two-parameter shooting code which matches boundary conditions between the pellet surface and the external plasma. The solutions resulting from this procedure are then compared with the assumptions made by Parks in deriving this relationship analytically.[7]

In the following sections, the basic assumptions in the low-Z evaporation model are reviewed and the two-parameter shooting calculation is outlined in Sec. II; the results of the two-parameter shooting calculation for various cases are compared with the assumptions in Sec. III. In Sec. IV, Parks' assumption, that local thermodynamic equilibrium (LTE) exists throughout the vapor, is tested through the estimation of the ionization lengths on the sonic surfaces for TEXT, TFTR, and CIT plasmas and some modifications in the low-Z model for TEXT are suggested. In Sec. V, the results of the normal and modified low-Z models are compared with results from the TFTR and TEXT experiments.

II. THE ASSUMPTIONS OF THE LOW-Z EVAPORATION MODEL AND THE TWO-PARAMETER SHOOTING CALCULATION

In his low-Z evaporation model,[4] Parks couples the sonic and pellet surface values of the electron heat flux using thermodynamical arguments to determine the flow parameters of the vapor. From these results, an analytical self-consistent model is derived between the evaporation rate at the pellet surface and the external plasma electron heat flux at the sonic surface (i.e., the transition between the interior subsonic and the exterior supersonic regions). The major assumptions he made were as follows:[4] (1) The vapor density in the subsonic region falls as $r^{-\alpha}$, where $5<\alpha<6$; (2) The ratio of the radius of the sonic surface to that of the pellet r_*/r_p is 1.33; (3) The temperature of the vapor at the pellet surface is 0.6 eV; (4) The Mach number of the vapor at the pellet surface is 0.5; (5) The conditions of local thermodynamic equilibrium prevail.

In the rest of this section, a two-parameter shooting calculation is described to test the first four assumptions. The fifth assumption will be treated in Secs. IV and V.

The two-parameter shooting calculation is similar to those previously used for hydrogen pellets,[7,8] except the boundary conditions on the pellet surface are now quite different due to the much larger heat of vaporization for carbon pellets (see Eqs. 20 and 21 of Ref. 4).

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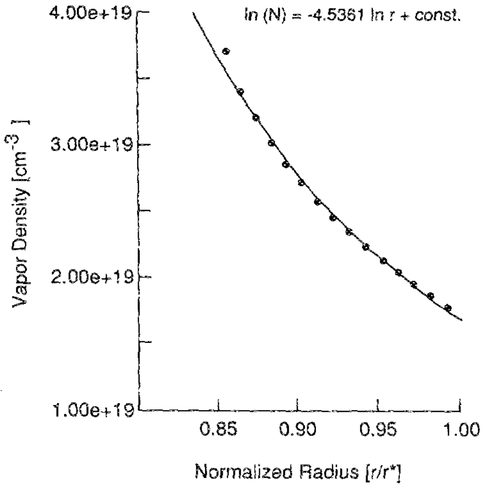

FIG. 1. Scaling of the vapor density with normalized radius inside the singular surface (normalized to the singular surface) for the self-consistent solution.

The two-parameter shooting calculation involves the choice of the singular surface parameters of external plasma electron energy E_*, external plasma electron heat flux q_*, and sonic radius r_*, and then using a shooting code to locate the plasma surface. The shooting code involves the propagation of $q(r)$ and $E(r)$ from the singular surface to the pellet surface based on the attenuation of $q(r)$ and $E(r)$ by the vapor which is a function of the mass density of the vapor $\rho(r)$. Thus the attenuation equations for q and E must be propagated inward as well as the fluid equations for the vapor. These fluid equations are the conservation of mass, momentum, and energy, where the latter includes the heat being deposited by the external plasma electrons self-consistently through $dq(r)/dr$. These equations are then propagated inward iterating on two parameters of the properties of the fluid on the singular surface: number density n_* and temperature T_*, until a solution is found where the boundary conditions at the pellet surface are satisfied.

III. THE RESULTS OF THE SHOOTING CODE IN COMPARISON WITH PARKS' ASSUMPTIONS

The results of a shooting code solution are shown in Fig. 1 and in Table I where r^* is the radius of the singular surface that lies just inside the sonic surface in this model and ζ_0^* is the ionization length at r^* for 0 to +1 charge transition (see below). $T_{e\infty}$ and $n_{e\infty}$ are the external plasma electron temperature and density respectively. Figure 1 illustrates that the vapor density dependency with radius does indeed follow a power law in the region inside r^*.

As can be seen from Table I, the assumptions made by Parks are in good agreement with the solution. Thus one would expect reasonable agreement between the predictions for the penetration of carbon pellets into magnetic fusion plasmas as long as Parks' fifth assumption of local thermodynamic equilibrium is valid.

IV. IONIZATION LENGTHS ON THE SONIC SURFACE

While the temperatures and densities in the interior region are sufficient for local-thermodynamic equilibrium (LTE) to exist,[9] this is not a sufficient condition for LTE. That is, there must be sufficient time for the collisional processes to establish this condition, and this time will be called the ionization time τ_{zi}. Since in the present problem, the vapor is flowing radially outward with a velocity v (at least in the weakly ionized inner region), this ionization time may be converted to an ionization length, $\zeta_z = v \times \tau_{zi}$. Here the subscript z refers to the transition from the Z to $Z+1$ charge state. To be meaningful, this length is then compared with a characteristic scale length for the problem such as the pellet radius r_p.

TABLE I. Parks' model vs self-consistent solution.

Parameter	Parks' model	Self-consistent solution
$n_{e\infty}$	···	1.81×10^{14} cm^{-3}
$T_{e\infty}$	···	2.68 keV
r_p	···	0.418 mm
α	5–6	4.536
r_*/r_p	1.33	1.68
r^*/r_p	···	1.32
T_p	0.6 eV	0.55 eV
M_p	0.5	0.30
ζ_0^*/r_p	0.0	0.021

From Table I, the assumption of LTE at the singular surface appears to be reasonable, since the ratio of ζ_0^*/r_p is small. To see how this parameter might change for other conditions, one can calculate this ratio on the sonic surface, using the results from Parks' low-Z model[4] and atomic physics.[9] For typical conditions and pellet radii for the TEXT, TFTR, and proposed for CIT devices, such calculations reveal that while LTE is a reasonable assumption for CIT, it breaks down for TEXT. That is, the ratio ζ_{0^*}/r_p is very small for CIT ($<10^{-5}$) and is very large for TEXT (>27). TFTR occupies a middle ground, where this ratio varies from around 1, for shots with a central plasma density of $5\times10^{13}/\mathrm{cm}^3$, to greater than 60 for a central plasma density of $2.25\times10^{13}/\mathrm{cm}^3$.

For TEXT and low-density TFTR shots, the effect of the external plasma electrons is more important than that of the vapor electrons. This can be seen in the ratio of ζ_{ox^*}/r_p, where ζ_{0x^*} is the ionization length for vapor ionization by the external plasma electrons, based on the cross sections for electron impact ionization of C^0.[10] For the devices being considered, the external plasma electrons play a negligible role for high-density TFTR shots and CIT in determining the charge-state distribution on the sonic surface (i.e., $\zeta_{0^*} \ll \zeta_{0x^*}$), whereas for TEXT and low-density TFTR shots, they are more important than the vapor electrons. But here, the ratio ζ_{0x^*}/r_p is of order 10 or greater, so a better assumption would be that the vapor is not ionized at all at this distance. This is the basis of a new model which will be used in the comparisons with the results of the experiments on TEXT discussed below.

V. COMPARISON OF THE MODEL WITH PELLET PENETRATION EXPERIMENT RESULTS

The results of some injection experiments on TFTR[11] and TEXT[5,6] are compared with the low-Z model in Table

TABLE II. Comparison of models with penetration experiments.

r_{p0} (μm)	v_p (m/s)	$T_{e0\infty}$ (keV)	$\lambda_p$exp (cm)	λ_pI (cm)	λ_pII (cm)	ζ_{0^*}/r_p
510[a]	260	4.4	54	52.3	51	1.44[c]
480[b]	375	5.7	54	61.5	60.8	15[d]
137	326	1.60	20.1	22.6	22.1	14[d]
158	349	1.68	21.9	24.2	23.7	12.4[d]
186	396	1.46	24.0	31.7	30.4	10.8[d]
198	390	1.60	25.0	30.2	28.9	10.3[d]
199	358	1.42	29.5	32.0	30.7	10.2[d]

[a]High-density TFTR shot.
[b]Low-density TFTR shot.
[c]Vapor electrons dominate ionization.
[d]External-plasma electrons dominate ionization.

II. r_{p0}, v_p, $T_{e0\infty}$, and λ_p are the initial pellet radius, its speed, the external electron temperature on the device axis, and the penetration depth, respectively. In the column marked λ_p EXP are the experimental results.[5,6,11] In the column labeled λ_pI are the results of the model where η, the fraction of the incident external electron heat flux that is shielded from the pellet surface by the cloud, is calculated at each step in the minor radius of the plasma being penetrated, and LTE is assumed to hold in the vapor cloud.[4] In the column labeled λ_pI are the results of the model where η is calculated at each radial step and the vapor is assumed to be un-ionized. This latter model appears to be the more reasonable for the TEXT and low-density TFTR shots, in view of the large ionization lengths encountered for these devices under these conditions.

The first two rows of Table II show the results of carbon pellet injection experiments into TFTR.[11] For the first case, a high-density shot, the minor radius a, was 83 cm; the electron density profile scales as $5.0\times10^{13}/\text{cm}^3\ [1-(r/a)^2]^{0.78}$; and the electron temperature profile scales as $\exp[-(r/a_t)^2]$, where a_t is 47 cm.[11] For the second row, a low-density TFTR shot, the minor radius of the plasma was 80 cm; the electron density profile scales as $2.25\times10^{13}/\text{cm}^3\ [1-(r/a)^2]^{1.0}$; and the electron temperature profile is again Gaussian, with $a_t = 42$ cm.[11]

For the last five cases listed in Table II, which involve the injection experiments into the TEXT device,[5,6] the minor radius of the plasma was 26 cm, the electron density profile scales as $4.0\times10^{13}/\text{cm}^3\ [1-(r/a)^2]^{0.87}$, and the electron temperature profile scales as[5] $[1-(r/a)^2]^{1.42}$. For a more thorough presentation of the impurity pellet injection experiments on TEXT, see Ref. 6.

As can be seen in the table, the models tend to overpredict the penetration depth in the cases where the ratio $\zeta_{0^*}/r_p \gg 1$, although the discrepancies are almost within the experimental uncertainties, especially if model λ_p II is used (which is appropriate for these high-ratio cases). That is, for the TEXT data, a 10% change in the $T_{e0\infty}$ results in a ∓2 cm change in λ_p for this model. Also for the TEXT data, uncertainties in the profiles such as a 50% change in the exponents of the profiles given above results in a ∓2 cm change in λ_p. Considering by how much these profiles are changing during the injection process,[5,6] effects that are well beyond the scope of the present model, the agreement between theory and experiment is quite good.

For the high-density TFTR shot, since $\zeta_{0^*}/r_p \approx 1$, neither model is appropriate, since the ionization fraction must lie between the LTE ($\zeta_{0^*} = 0$) and un-ionized ($\zeta_{0^*} = \infty$) results of models λ_pI and λ_pII, respectively. Therefore the "true" result of this theory for the predicted penetration depth λ_p must lie in between 51 and 52.3 cm, which is probably well within the uncertainties in the experimental values. While this is an encouraging result, several more shots into a high-density TFTR plasma[11] are needed to test the model completely.

VI. CONCLUSIONS

The low-Z model of Parks[4] appears to be in reasonable agreement with the results of a self-consistent two-parameter shooting-code solution. The assumption that LTE prevails in the inner vapor region appears to be fine for predicting the penetration of carbon pellets into the higher-density experiments such as high-density TFTR shots and CIT, but it appears to break down for the conditions on the TEXT and low-density TFTR experiments. Assuming that no ionization occurs in the inner region of the carbon vapor gives better agreement with the TEXT and low-density TFTR results. Thus, on the basis of the data available, in determining the design requirements for a carbon pellet injector for CIT, which is designed to have even higher densities than TFTR, the low-Z model[4] should do a good job in predicting the penetration on that device, that is, unless effects not considered here, such as magnetic shielding,[12] play a role.

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[1] E. Marmar, "Lithium Pellet Experiments on the Alcator-C Tokamak," presented at the Workshop on Alpha-Particle Diagnostics on CIT, Princeton Plasma Physics Laboratory, Princeton, NJ, 3–5 June 1987.
[2] J. L. Terry (private communication, January 1989).
[3] R. K. Fisher, J. S. Leffler, A. M. Howald, and P. B. Parks, Fusion Tech. **13**, 536 (1988).
[4] P. B. Parks, J. S. Leffler, and R. K. Fisher, Nucl. Fusion **28**, 477 (1988).
[5] M. L. Walker, F. C. Anderson, S. C. McCool, K. R. Carter, T. K. Herman, and E. Marmar, Bull. Am. Phys. Soc. **33**, 2024 (1988).
[6] M. L. Walker, S. C. McCool, D. L. Brower, M. E. Austin *et al.*, "Impurity Pellet Ablation in TEXT," University of Texas Fusion Research Center Report No. 365, June 1990.
[7] P. B. Parks and R. J. Turnbull, Phys. Fluids **21**, 1735 (1978).
[8] F. S. Felber, P. H. Miller, P. B. Parks, R. Prater, and D. F. Vaslow, Nucl. Fusion **19**, 1061 (1979).
[9] R. W. P. McWhirter, in *Plasma Diagnostic Techniques*, edited by R. H. Huddlestone and S. L. Leonard (Academic, New York, 1965), Chap. 5.
[10] G. H. Dunn, in *Electron Impact Ionization*, edited by T. D. Maerk and G. H. Dunn (Springer, Vienna, 1983), Chap. 8.
[11] J. L. Terry (private communication, June 1990).
[12] P. B. Parks, Nucl. Fusion **20**, 311 (1980).