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Linda L. Vahala
Old Dominion University, lvahala@odu.edu

Glenn Gerdin
Old Dominion University

A. G. El Cashlan
Old Dominion University

Paul Parks

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Self-consistent determination of low-Z_a pellet ablation and pellet penetration

Linda Vahala, Glenn Gerdin, and A. G. El Cashlan[a)]
Department of Electrical and Computer Engineering, Old Dominion University, Norfolk, Virginia 23529

Paul Parks
GA Technologies Inc., San Diego, California 92138

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The ablation dynamics of LiT pellets are solved self-consistently over a modest range of parameters using a surface dissociation model. The self-consistently determined parameters are then used to modify the standard low-Z pellet penetration codes. Since LiT pellets have certain advantages over carbon [in particular, Li conditioning of the walls and T for refueling a D–T reaction], the penetration of LiT into fusion plasmas is considered.

I. INTRODUCTION

The study of low-Z impurity pellet ablation in high-temperature plasmas has been a subject of great interest from the viewpoint of fusion diagnostics.[1,2] However, there are considerable difficulties in obtaining adequate pellet penetration into the fusion core. Because of carbon's high sublimation energy (7.5 eV/atom), it penetrates farther than other low-Z materials. Lithium pellets, although they have a lower sublimation energy (1.6 eV/atom) and hence a weaker penetration depth than carbon, are useful in wall conditioning. Recently, McCool *et al.*,[3] have suggested the use of LiT pellet injection into deuterium plasmas (the sublimation energy of LiT is 2.2 eV/atom, with dissociation energy of 2.5 eV/molecule). These pellets allow fusion refueling and are not cryogenic. Moreover, because of LiT's high tensile strength, higher pellet injection velocities are possible and this will aid in deeper plasma penetration.

The standard model[4] used to describe low-Z pellet ablation is a phenomenological model which focuses on the physics of the phase transition at the pellet surface. Certain assumptions have to be made on the transonic ablation flow. From this model, a pellet penetration algorithm was developed for low-Z pellet ablation. The predictions of this algorithm could be sensitive to certain input parameters which can only be estimated in the low-Z model.

It is not clear, especially for LiT pellets, how close these estimated input parameters are to the actual values. It is one of the objectives of this paper to determine these input parameters from a self-consistent (sc) solution for the transonic flow region and then to test their effects on the pellet penetration code.

Some of the important assumptions that are made in the low-Z phenomenological model[4] are (i) the local Mach number of the ablation cloud at the pellet surface $M_1 \approx 0.5$; (ii) the ablation cloud density in the subsonic region decays from the pellet surface $n_{c1}(r) \approx r^{-\alpha}$, with $5 < \alpha < 6$; (iii) the ablation cloud temperature at the pellet surface, $T_1 \approx 0.6$ eV; (iv) the ratio of sonic radius to the pellet radius, $r_*/r_0 \approx 1.33$; (v) local thermodynamic equilibrium (LTE) holds throughout the entire ablation cloud; and (vi) the supersonic flow $(r > r_*)$ is isothermal.

The rate at which the pellet surface is being ablated is determined from the phase transition boundary conditions at the pellet surface, and is given by[4]

$$\frac{dr_0}{dt} = -\frac{f_B \eta q_\infty}{n_0\{\Delta H + \gamma T_1[M_1^2/2 + 1/(\gamma-1)]\}} \tag{1}$$

(subscript 0 refers to the solid material, while 1 refers to the vapor cloud at the phase transition boundary) n_0 is the solid pellet number density, ΔH is the sublimation energy of the pellet, and γ is the ratio of specific heats. f_B is the magnetic screening factor[5] which reduces the energy flux reaching the pellet due to anisotropic magnetic field effects. This reduction depends on the ratio of pellet radius to the average electron gyroradius and typically $0.5 < f_B < 0.7$. The heat flux attenuation factor $\eta = q_1/q_\infty$, where q_∞ is the background plasma electron heat flux and q_1 is the heat flux at the pellet surface. The term inside the square brackets in Eq. (1) is usually approximated by $\Delta H + 2.7T_1$, based on assumption (i).

The pellet radius $r_0(t)$, r_{pl}, is then determined by integrating Eq. (1) for given (constant) pellet speed v_{pl} and specified background plasma density $n_{e0}(r)$ and temperature $T_{e0}(r)$ profiles. In most pellet penetration codes,[4,3] the input parameters are typically f_B, T_1, M_1, α, and r_*/r_0. These codes then solve iteratively for the attenuation factor η after which Eq. (1) can be integrated to determine the pellet penetration.

Here, over a modest range of parameters, we determine sc solutions to the low-Z model. From these sc solutions, the input parameters for the penetration codes are determined and the sensitivity of the standard codes on these parameters can be tested.

II. SELF-CONSISTENT (sc) LOW-Z MODEL

A sc solution is determined from the cloud continuity, cloud momentum, cloud energy, plasma heat flux and plasma energy equations, and two boundary conditions that determine the location of the pellet surface. The cloud energy equation exhibits a singularity in the subsonic region and this can be handled by starting the radial inward

[a)]Present address: NASA Langley Research Center, Hampton, VA 23665.

TABLE I. Self-consistent LiT parameters.

r_{pl} (mm)	f_B	T_1 (eV)	M_1	η	α	f^*	$n_{e\infty}$ (+13)	$T_{e\infty}$ (keV)	B_0 (kG)	r_*/r_{pl}
0.80	0.66	0.31	0.41	0.22	4.3	0.31	8.98	6.53	20.4	1.33
0.74	0.66	0.27	0.38	0.22	4.4	0.24	8.97	7.68	23.9	1.33
0.68	0.65	0.25	0.38	0.25	4.4	0.18	8.99	8.69	30.0	1.33
0.62	0.65	0.24	0.38	0.26	4.2	0.16	9.47	9.83	33.5	1.33
0.56	0.65	0.24	0.38	0.28	4.5	0.11	9.72	10.8	40.9	1.33
0.49	0.65	0.21	0.38	0.33	4.5	0.08	10.00	11.74	48.6	1.33

propagation at this singular surface, as done for hydrogen pellets.[6] The initial conditions for the solutions of these differential equations are then varied until the two phase transition boundary conditions are satisfied. These boundary conditions have been derived in the low-Z phenomenological model.[4] In obtaining an inner solution, T_1, M_1, α, and η are determined self-consistently and can readily be checked with those values assumed in the low-Z model. The background plasma profiles n_{e0} and T_{e0} are determined only *after* this subsonic problem has been solved.

Earlier, we have presented our results for carbon[7] and found very good agreement with the assumptions of the phenomenological model. Typically, it has been found that the pellet penetration codes are in good agreement with experiment carbon ablation results, particularly in hot plasmas.

For simplicity, the LiT vapor is assumed to dissociate at the pellet surface. On assuming surface dissociation, one is in essence increasing the sublimation energy by the 2.5 eV/atom dissociation energy. If volumetric dissociation is considered then this effect is diluted since the electrons striking the pellet surface are constrained to magnetic field lines whereas the vapor is not, until it is appreciably ionized. In Table I, we list some relevant parameters determined from a particular sequence of self-consistent LiT pellet solutions. Note that there are some differences with

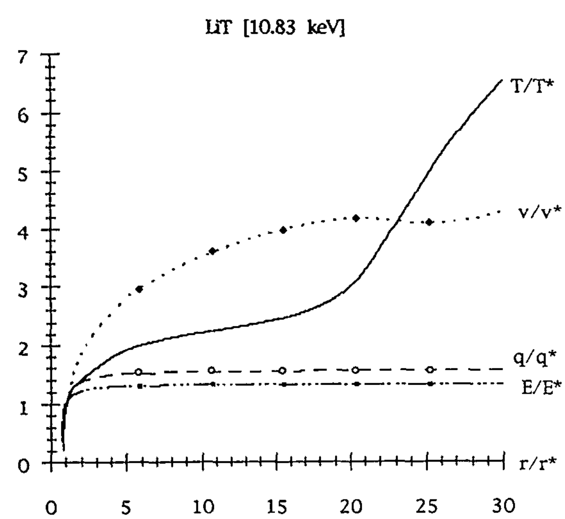

FIG. 1. Normalized radial profiles of the self-consistent (sc) LiT solution for the 10.83 keV case. v and T are the ablation cloud velocity and temperature. q and E are the background electron heat flux and energy. These quantities are normalized to their values at the sonic surface.

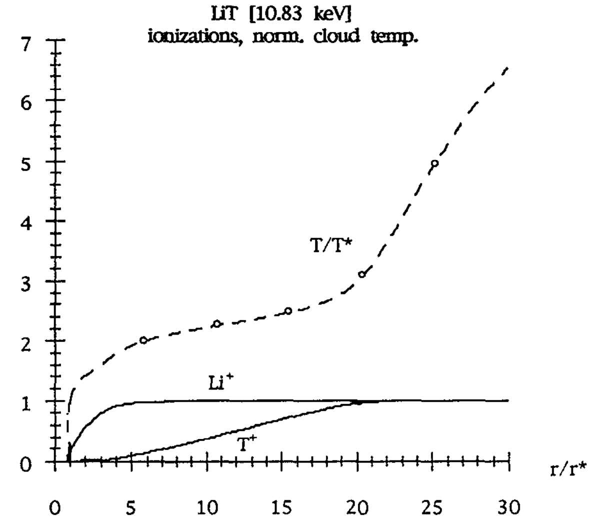

FIG. 2. Ionization and normalized temperature profiles in the LiT ablation cloud. Note that during the tritium ionization, the cloud temperature is relatively flat.

values assumed in the low-Z phenomenological model (in particular low-Z parameters $T_1=0.6$, $M_1=0.5$, $5<\alpha<6$). Close to the pellet surface, the cloud density falls off very rapidly and then it decays following a power law. In Fig. 1, the cloud velocity (v), cloud temperature (T), background plasma flux (q), and electron energy (E) are shown, normalized to their sonic values. The Li^+ ionization occurs

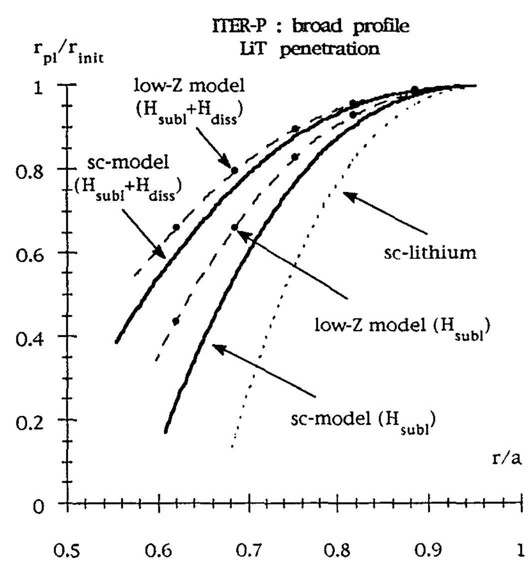

FIG. 3. 3 mm LiT pellet penetration into an ITER-P plasma with broad plasma profiles, Eq. (2). Pellet velocity is 8 km/s. The input parameters are those determined from sc solutions. Also shown are the results from the application of the low-Z model input parameters (see Sec. I). Self-consistent input parameters, however, are used for the Li pellet (which for direct comparison with LiT has the same injection speed and initial radius). Plots are shown both with and without the effects of surface dissociation [see Eq. (1)]. The solid curves are for the sc solution. The –●–●– curves are those for the input parameters from the low-Z model. The dashed curve is for sc solution for Li. Since the surface dissociation model overestimates the cloud shielding, the actual penetration of LiT should be bounded by the curves with and without the dissociation energy sink (i.e., $H_{subl}+H_{diss}$, and H_{subl}, respectively).

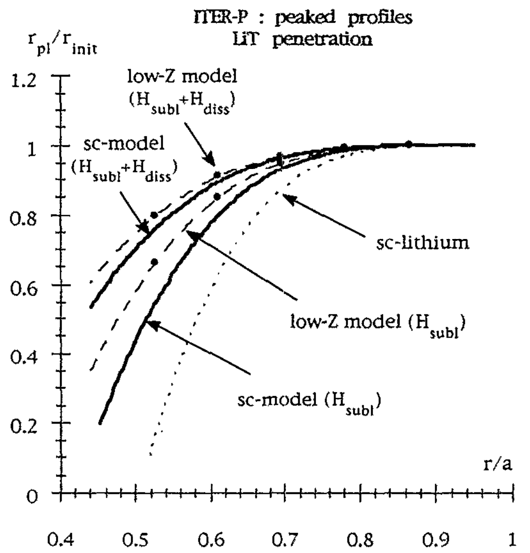

FIG. 4. As for Fig. 3, but now with peaked ITER-P plasma profiles, Eq. (2).

rapidly and this is followed by T^+ ionization, as expected (Fig. 2). Note that the temperature profile in the supersonic region ($r/r_* > 1$) remains basically constant till the energy sink of T^+ ionization is saturated ($r/r_* \approx 20$). There is then a substantial increase in the vapor temperature.

The standard low-Z pellet penetration code can now be suitably modified by using input parameters (T_1, M_1, α) as inferred from our sc solutions (Table I). Here, we consider pellet penetration into a burning plasma [ITER-P: $n_{e0} = 2.0 \times 10^{14}$ cm^{-3}, $T_{e0} = 17$ keV] with Maxwellian electrons and two plasma profiles[3]

$$\begin{aligned} \text{broad: } & n_{e\infty}(r) = n_{e0}[1 - r^2/a^2]^{1/2}, \\ & T_{e\infty}(r) = T_{e0}[1 - r^2/a^2], \\ \text{peaked: } & n_{e\infty}(r) = n_{e0}[1 - r^2/a^2], \\ & T_{e\infty}(r) = T_{e0}[1 - r^2/a^2]^2, \end{aligned} \tag{2}$$

where a is the plasma minor radius. Also plotted in Figs. 3 and 4 are the results from using the standard parameters in the low-Z model (Sec. II). Numerically, we find that T_1 is a key parameter for the penetration code [see also Eq. (1) with the explicit T_1 factor in the denominator]. Also shown in these figures are (i) the case of no surface (or volume) dissociation since these curves are a lower bound on LiT pellet penetration, and (ii) Li pellet penetration, as determined from the standard low-Z model.

III. CONCLUSIONS

The spherically symmetric ablation of LiT pellets is examined self-consistently over a modest range of parameters by solving the full cloud dynamics and phase transition boundary conditions that determine the pellet surface. The vapor cloud parameters at the pellet surface differ somewhat from those assumed in the low-Z model.[4] LiT pellet penetration into a fusion plasma is then determined from the low-Z penetration code after changes to certain pellet surface parameters are made from the self-consistent database for LiT pellets. For pellet penetration, the most important parameter is the surface temperature T_1.

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