CIT ALPHA EXTRACTION AND MEASUREMENT

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Dr. Glenn A. Gerdin and Dr. Linda L. Vahala

Department of Electrical and Computer Engineering

Old Dominion University

Norfolk VA 23529

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ABSTRACT

In the last year of the period of active funding (ending in the fall of 1992), progress in the investigation of the low-Z pellet-plasma interaction was been made in two areas: 1) the calculations to determine a self-consistent solution to the region inside the sonic surface were extended to include boron and tritium tritide pellets as well as lithium and carbon, 2) a slab model for power losses due to line radiation has been included in the overall energy balance for lithium clouds. This has led to the identification of four candidate processes, which could account for the differences between the results from our calculations and the lengths of the Li^{+1} clouds observed during pellet penetration experiments on TFTR, have been identified. These processes are line-radiation from the cloud holding down its temperature, the charging up of the cloud reducing the incident hot electron flux from the plasma, the cooling of the plasma in contact with the cloud, and the reduction of the heat flux of the incident electrons to the cloud due to the backscatter of these electrons from the cloud (i.e., albedo). However, while each of these effects was explored individually, all these effects could not be incorporated into a single computer code during the period of active funding.

Previously, self-consistent equilibrium and non-equilibrium charge-state models were formulated for the spherical expansion of low-Z pellet vapor as an inviscid perfect gas of constant ratio of specific heats being heated volumetrically by the incident electrons of a thermonuclear plasma. The two models were found to be in agreement in the region where the ratio of the ionization length ζ_j to pellet radius r_p is less than one, but a single parameter, such

as the magnitude of this ratio on the sonic surface, was insufficient to determine whether an equilibrium model would be valid for all regions of the ablatant for carbon pellets. Thus a non-equilibrium model was necessary to model the outer regions of the ablatant cloud even for thermonuclear plasma conditions when the cloud is very dense. Also the effect of the ionization of the ablatant by the incident plasma electrons was found to be 10% or less for even the C^{+3} region in the thermonuclear regime. Flow along the magnetic field is treated as a constraint in the cross-sectional area of the flow, setting the channel radius to that which is observed.

I. Progress during the last year of funding (to fall 1992).

Background

The objective of the research program is to provide detailed modeling of the impurity-pellet injection experiments being performed under the guidance of Dr. R.K. Fisher of General Atomics Inc.(GAI), to put the simulation model on a firm basis for predicting the performance of the proposed alpha-particle diagnostic¹ using the ablation clouds of the impurity pellets as a charge-exchange medium for alpha-particle extraction. This simulation effort is also supported on a theoretical-conceptual basis by close collaboration with Dr. P.B. Parks of GAI. The experimental data base for comparison with the simulations is also being expanded by the inclusion of data being made available by Drs. J. Terry, E. Marmor, and J. Snipes of M.I.T. from their impurity-pellet injection experiments on the Tokamak Fusion Test Reactor (TFTR), and that soon to be obtained by Dr. R.K.Fisher's experimental team on TFTR.² These latter data are especially important, in that for the first time, the performance of the impurity-pellet alpha diagnostic will be tested by measuring the minority-species heated ³He tail in a alpha-particle diagnostic simulation experiment.²

The modeling of the interaction of the alpha (or ³He) particles with the ablation cloud is straight-forward as long as the charge-change cross sections are known,¹ but they do place restrictions on the nature of the ablation cloud necessary for the interpretation of the results to be straight-forward as well. Namely, that the cloud, in its thickness in the direction perpendicular to the applied magnetic field $t_{\perp}$ (roughly the direction in which the alphas will travel that will be extracted by this diagnostic technique) be thicker than that required for the alpha particles to be in charge-state equilibrium, $t_{\alpha eq}$, but thinner than the thickness where the alphas will experience

significant energy loss, t_{E_k} . Under these conditions, there will be a one-to-one correspondence at each alpha energy between the neutralized alpha flux hitting the wall and the doubly ionized alpha flux incident on the ablation cloud. For 1 MeV alpha particles,¹ $t_{\alpha eq}$ is around $10^{16}/\text{cm}^2$, and t_{E_k} is about $10^{19}/\text{cm}^2$, so in the simulations of the impurity-pellet injection experiments, t_L is of great interest.

Another feature of the ablatant cloud, important for straight-forward interpretation of the experimental data, is that there be an extended region of a given charged species of the ablatant in the cloud. This requirement is due the dependence of the ratio of the neutral flux to doubly-charged alpha flux, $F_0(E_\alpha)$ on the charge-change cross sections which are in turn dependent upon the charged species with which the alphas interact. Therefore, the existence of an extensive region of only one ablatant charge species, would make the interpretation of the experimental data simpler. Since all of the impurity pellet materials (i.e. Li, B, C) will go through a Helium-like electronic state on being totally stripped, and since this charge state is a closed shell, it has a much higher ionization potential than any of the lower ionized states, the Helium-like charge state may be expected to persist; this property may make it possible for simplified interpretation of the experimental results.

Thus, the modeling of the impurity-pellet interaction to determine t_L and the distribution of the various charged species of ablatant is crucial to the prediction of the performance of the impurity-pellet alpha-particle-diagnostic concept. Hence, our simulation efforts have focused on the impurity-pellet plasma interaction to see if the ablation cloud will exhibit these properties.

The Present Model: A. The Interior Region.

A self-consistent (SC) solution to the interior problem (i.e., that region between the sonic surface and the pellet surface) is determined from the cloud continuity, momentum, and energy equations, where the plasma electron heat flux acts: 1) as a volumetric heat source through electron slowing down losses, and 2) as a heat source at the pellet surface driving the ablation rate which in turn is the particle source for the cloud. A self-consistent solution occurs when the electron heat flux at the pellet surface, which has been attenuated by the cloud thickness, is just sufficient to generate an ablation rate consistent with that cloud thickness. Obtaining these solutions is difficult, because the cloud energy equation exhibits a singularity in the subsonic region; this problem is treated by starting the radial inward propagation at this surface, as was done for hydrogen pellets.³ The initial conditions for this inward propagation are varied until two boundary conditions are satisfied. These boundary conditions have been derived in the low-Z phenomenological model.⁴ In obtaining an inner solution, four parameters of the phenomenological model: T_1 , M_1 , α , and η , are determined self-consistently; these parameters are the temperature of the vapor at the pellet surface, the Mach number of the cloud at the pellet surface, the exponent of the power law for cloud density decay with radius, and the plasma heat flux attenuation factor at the pellet surface. These parameters can be readily compared with those assumed by in the phenomenological model, and used in that model to get more self-consistent plasma-surface conditions and ablation rates. The background plasma quantities n_{e0} and T_{e0} corresponding to these solutions are determined after the subsonic problem has been solved by propagating the equations to the exterior until the mean energy and heat flux stop being attenuated significantly.

The procedure outlined above was implemented on the IBM 3060 at Old Dominion University for the impurity pellet materials of lithium, boron, and carbon; this results in a self-consistent inner solution, so that the pellet radius r_p is known as well as the flow properties of the ablatant between the pellet radius and the radius of the singular surface r_s . The results of these calculations were published⁵ in Nuclear Fusion in March of 1994, and a copy of this paper is included here as Appendix A. Also the results of an earlier self-consistent solution,⁶ not based on the techniques of reference 3 are included here as Appendix B. The results of the two techniques are comparable, but the techniques of the former were more easily incorporated into our code modeling the region of the cloud exterior to the sonic surface, so they are the ones used at present.

Pellet Penetration into Tokamak Plasmas

Earlier, we have presented our results for carbon^{7,8} 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 experimental results for carbon pellets in terms of pellet penetration, particularly for hot plasmas. Using the SC solutions we obtained for lithium for these parameters, in a pellet-penetration code, resulted in close agreement between the code results and experiment in term of distance penetrated by the pellet. This is shown in the following Table.

Table I: Comparison of Lithium Pellet Penetration of TFTR
and Our Penetration Code Predictions.

The minor radius $a = 0.80$ m, and the last closed flux surface $R_0 = 2.45$ m.⁹

Shot #	pellet velocity	$T_e(R_{\text{penx}})$	$n_e(R_{\text{penx}})$	R_{penx} exp.	R_{penh} ODU code
	[m/s]	[keV]	[$10^{13}/\text{cm}^3$]	[m]	[m]
52197	750	2.3	6.8	2.69	2.70
52198	710	2.1	6.6	2.72	2.67
52199	590	2.1	6.7	2.72	2.72
52236	610	1.6	7.3	2.67	2.65
52241	580	2.3	7.0	2.83	2.85
52242	590	2.3	7.1	2.81	2.84

These results are show better agreement than when the original estimates for these parameters are used,⁴ although the original parameters do not do too badly. These techniques have been recently extended to boron and lithium tritide pellets. A recent paper⁶ describing the work on LiT pellets, is included as Appendix B.

Thus these inner solutions can be used in two ways: 1) as improved input parameters for pellet penetration codes, and 2) to calculate more self-consistent sonic-surface parameters, to be used as initial conditions for our calculations of the properties of the cloud in the exterior region, which is of such importance in the modeling of the alpha-particle diagnostic technique.¹

The Present Model: B. The Exterior Region.

Our present model is really an extension of previous work^{3,10,11} based on a steady-state, spherical (hence one-dimensional) expansion of hydrogen ablatant as an ideal gas, where ionization is treated self-consistently in the energy equation, but assumed to be in charge-state equilibrium. This model, through considerable effort on our part, now includes, a non-

equilibrium ablatant charge-state model to account for the finite ionization time, ionization by external plasma electrons, and simulates the flow along the magnetic field by placing a constraint on the cross sectional area of the flow.⁸ Reference 8 describes this model, and being a good summary of our earlier work, is included here as Appendix C.

The model gives reasonable agreement with the observed densities of the various charge-state regions of lithium pellet injection experiments on TFTR by Drs. Terry, Marmor, and Snipes, but predicts the length l_B of the Li^{+1} charge-state region along the magnetic field to be about 3 cm, which is only about one-tenth of the observed length of Li^{+1} line-radiation region.¹² The recent addition¹³ of a collisional-radiation model for line emission power losses in slab geometry, changes these predictions only slightly; therefore, the inclusion of radiation, while obviously important, appear not to be able to reconcile the differences between the results of our models and experiment. In comparison with other experiments, our model predicts the scaling of l_B for the C^{+2} and C^{+3} line-emission regions observed by R.K. Fisher's group in TEXT, but is somewhat off in absolute value.¹⁴ Part of this discrepancy is no doubt due to the apples-and-oranges-type comparison between the length of charge-state regions predicted by the model with line-emission regions from the same charge state observed experimentally.

The Slab-Geometry Line-Emission Model.

Since the densities of the charge-states in the cloud are on the order of $10^{16}/\text{cm}^3 < n_Z < 10^{17}/\text{cm}^3$, and the cloud radii are on the order of a few centimeters, the resonant lines, which involve transitions from the ground state, are optically thick.¹⁵ Also, the electron excitation time τ_{Z*} between the states above the ground state Z is so short under these conditions, that the excited states can be in LTE with each other and the next ionized state $Z + 1$. The ground states,

however, are not in equilibrium, because the first excited state lies between 75 % (H-like) to 80% (He-like) of the ionization potential above the ground state. This is shown in Table II, for typical cloud conditions, where T_e for the cloud is taken to be 2 eV to be consistent with the results of our calculations.¹³

Table II.: Excitation rates for various transitions of Li^{+1} and Li^{+2} .

The plasma parameters of the cloud are $n_e = 2.5 \cdot 10^{16}/\text{cm}^3$, $T_e = 2 \text{ eV}$, and $v = 0.5 \cdot 10^6 \text{ cm/s}$.¹³

Ion	Transition	ΔE	Excitation $\langle \sigma v \rangle$	τ_{Z*}	Excitation Length:
		[eV]	[cm^3/s]	[s]	$v\tau_{Z*}$ [cm]
Li^{+1}	$2s^1S - 3s^1S$	8.5	$2.8 \cdot 10^{-9}$	14.2 ns	$7 \cdot 10^{-3}$
Li^{+2}	$2s - 3s$	16.9	$2.8 \cdot 10^{-11}$	1.42 μs	0.7
Li^{+2}	$3s - 4s$	5.9	$1.7 \cdot 10^{-8}$	2.3 ns	$1.2 \cdot 10^{-3}$

Thus, even at 2 eV, the equilibration times are short for all excited states, except the 2s state of Li^{+2} . Even this state has a comparatively short excitation length, when compared with the total flow length of 10's of centimeters. So in the following, the excited states of Li^{+1} are assumed to be in LTE with the ground state of Li^{+2} , and the excited states of Li^{+2} are assumed to be in equilibrium with Li^{+3} , as is consistent with the collisional-radiation model.¹⁶

Ignoring stimulated emission, which is justified for $h\nu > kT_e$,¹³ the line emission intensity, for the p to q transition, from the surface of the optically thick cloud $I(\nu)$, is given by the ratio of $J(\nu)/\chi(\nu)$:

$$I(\nu) = J(\nu)/\chi(\nu) = n(Z,p) \omega(Z,g) 2 h \nu^3 / [n(Z,g) \omega(Z,p) c^2], \quad 1)$$

where $J(\nu)$, $\chi(\nu)$, $n(Z,p)$, $\omega(Z,g)$, $n(Z,g)$, and $\omega(Z,p)$, are the coefficient of emissivity, that of absorption, the number density of the p state of charge state Z, the statistical weight of the

ground state, the number density of the ground state, and the statistical weight of the p state, respectively. In deriving equation 1) it has also been assumed that the source function is independent of frequency, which has also been shown to be a good approximation.¹⁶

In our calculations, the ionization rate equations are used to calculate the ground-state populations, and the excited state populations for the Z^{th} charge state, are related to the $n(Z+1, g)$ population by the LTE condition:

$$n(Z, p) = n(Z+1, g) n_e \omega(Z, p) \exp\{[\Phi_Z - E(p, g)]/kT\} / [\omega(Z+1, g)^2 \{2\pi m k T / h^2\}^{3/2}], \quad 2)$$

where Φ_Z , and $E(p, g)$ are the ionization potential of the Z^{th} charge state and the energy of the p excited state, respectively.

For the resonant lines, the intensity given by equation 1) is taken over a Doppler-broadened line width, and the power loss is averaged over the cross section of the flow column. For the non-resonant lines, the excited population densities of equation 2), are simply multiplied by their transition probabilities, the line energy, and the Doppler-broadened line width. Doppler broadening is valid for the short-wavelength transitions being considered here, i.e.: $168.7 \text{ \AA} < \lambda < 199.3 \text{ \AA}$, for the resonant lines of Li^{+1} , and $104.1 \text{ \AA} < \lambda < 135 \text{ \AA}$ for those of Li^{+2} .

The inclusion of this power loss into our lithium-pellet exterior-cloud code, using pellet radius and plasma conditions consistent with TFTR lithium-pellet injection experiments,¹⁴ resulted in the little apparent change for the case without radiation however since the heat deposition by the incoming plasma electrons overwhelms this effect. So the length of the Li+1 part of the ablatant clouds in TFTR are observed to be 30 cm long {Snipes} along the magnetic field, where our model predicts only 3 cm for these conditions.

Another possible explanation.

One potential reason for this discrepancy is the assumption in the model³⁻⁸ the incident plasma electrons when they are scattered ninety degrees, deposit all of their remaining energy locally. However, at this point, they still have considerable energy remaining and undergo considerable pitch-angle scattering on slowing down on the cloud material. Preliminary studies, showed that the standard deviation in final location (when their energy was that of the particles in the cloud) from the point in the cloud where the ninety degree scattering event occurred, was on the order of the cloud thickness.

If one assumes that since one-half of these particles are scattered toward the pellet and one-half away, that maybe that the contribution to the cloud heating by those electrons having scattered to ninety degrees is reduced by a factor of one-half, one now finds the lengths of the Li^{+1} clouds predicted by the model, for the conditions described above increase to 21 cm instead of 3 cm, being comparable to the length of those observed⁹ of 30 cm. Since this argument is of a speculative nature, it is only provided here as food for thought, in case some future scientist should decide to follow up on these calculations.

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APPENDIX A

Journal article —
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APPENDIX B

Journal article. Removed
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APPENDIX C

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