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PELLET ABLATION AND ABLATION MODEL DEVELOPMENT *

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INTRODUCTION

A broad survey of pellet ablation is given, based primarily on information presented at this meeting. The implications of various experimental observations for ablation theory are derived from qualitative arguments of the physics involved. The major elements of a more complete ablation theory are then outlined in terms of these observations. This is followed by a few suggestions on improving the connections between theory and experimental results through examination of ablation data. Although this is a rather aggressive undertaking for such a brief (and undoubtedly incomplete) assessment, some of the discussion may help us advance the understanding of pellet ablation.

Engelmann presented a summary of pellet fueling issues in future devices [1]. The issue most closely connected with pellet ablation is that of pellet penetration. Partial pellet penetration and deep penetration have different implications for technology development. Getting beyond the scrape-off layer and the poorly confined edge region is a fairly straightforward task and can be accomplished with present technology. This can be used to improve on the fueling efficiency of gas injection. Deep penetration, as seen in many experimental results, provides added control over the plasma density profile and access to improved confinement regimes. ASDEX-results indicate that partial pellet penetration gives some confinement benefits [2], but JET results seem to indicate that the maximum benefits are gained with central fueling [3]. The relationship between pellet penetration and confinement is still a fairly open question, covered in the summary by Lackner [4]. We may not have any conclusive answers on the relationships between fueling profiles and confinement, however, until we better understand the basic plasma transport processes.

The means of improving pellet penetration are pellet size and pellet velocity. The pellet size is limited by physics — by how large a mass increase the plasma can tolerate. The pellet velocity is limited by technology [5]. So these two parameters must be played off against each other to reach optimal fueling conditions, but one involves physics and the other, technology. To quantify the trade-offs between pellet size and velocity, a better understanding of the ablation process is needed. We would like to be able to predict pellet penetration and particle source profiles in planned experiments and to provide guidance for technology development. So the basic question we come down to is how pellet ablation and penetration scale with pellet size and velocity.

EXPERIMENTAL OBSERVATIONS AND IMPLICATIONS

Various experimental observations can be used to provide clues to the important considerations in pellet ablation physics. Many of these features are widely observed. Some have widely accepted explanations, while others have several possible interpretations. In many cases, quantified comparison between theory and experiment is not yet possible.

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Curved Pellet Trajectories

One of the earliest observations was that pellets do not necessarily travel in a straight line. The explanation for this was given many years ago and is now used as the basis for electron beam acceleration of pellets [6]: asymmetric illumination of the pellet causes a rocket effect. When the incident fluxes to the pellet co and counter to the magnetic field are unbalanced, the nonuniform evaporation of the pellet surface accelerates the pellet in the direction of the imbalance of the forces. It is less of an effect in large tokamaks than small tokamaks because of a combination of larger pellet sizes and smaller perturbation of the electron distribution by the applied electric field. The effect is most notable in the ZT-40M reversed field pinch, where reorientation of the injector was required to improve control over the mass deposition [7]. The importance of the magnetic field and plasma distribution functions is implied by this observation. It emphasizes that pellet ablation models must consider nonuniform illumination and anisotropic distribution effects. Neutral shielding models take into account the restriction of the incident electron flux to the cloud by using $2\pi r_p^2$ for the exposed surface area rather than the $4\pi r_p^2$ of a sphere. Otherwise, a uniform spherical expansion of the cloud is generally assumed — appropriate for uniform illumination and expansion into a vacuum.

Reduction of H_α at Magnetic Axis

ISX-B experiments were the first in which pellets penetrated to magnetic axis, where a very large dip was seen in the ablation rate. The effect has been seen in many other experiments since then. The obvious explanation is that there is a geometric singularity at the magnetic axis which limits the amount of plasma energy available in the ablation process. The implication is that the magnetic geometry is very important in the ablation process — specifically, that the plasma cannot always be treated as an infinite medium. Ablation models that account for finite plasma volume are said to include self-limiting ablation effects, because as ablation proceeds the temperature of the remaining plasma is reduced and further ablation is restricted.

H_α Fluctuations

The explanation of the large dip in H_α signals at the magnetic axis has been extended to cover small fluctuations in H_α signals by arguing that the plasma volume connected to the pellet is restricted at rational flux surfaces. The argument has been largely qualitative because of the difficulty in including all the proper geometry and kinetics. Because of the large number of fluctuations, relatively high-order rational surfaces must be considered. Pégourié [8] has recently developed a comprehensive model of the effect of rational surfaces, including the lack of depletion of trapped electrons because of toroidal drift, and concludes that the magnitude of the dips at rational surfaces can only be explained if there is a flattening of the q profile in the vicinity of each rational surface. In reality, the effect may be even more complicated. All experiments use cylindrical pellets, which tumble as they pass through the plasma. Because the illumination of the pellet is primarily on surfaces normal to the magnetic field, the pellet exposes a fluctuating cross-sectional area to the plasma. The magnitude of the usual H_α fluctuations is generally consistent with the different cross-sectional areas exposed to the plasma by a tumbling cylinder. Another possibility that has long been recognized is that there may be hydrodynamic instabilities in the neutral or ionized clouds. Lengyel has recently developed a time-dependent, single-cell Lagrangian model for the expansion of the cold ablatant plasma that may be used to address compressive oscillations as a possible source of the fluctuations [9]. It is likely that some combination of these effects is necessary to explain the oscillations: rational flux surfaces and tumbling introduce a time-dependent source and pellet cross-section that cause oscillations in the hydrodynamic solution, which may fail to reach a true steady state and appear largely random in magnitude. The very large dips seen in the H_α signals may still be associated with islands or very low order rational surfaces. Passing through an X-point or the center of a rotating island would make the magnitude of the dip vary considerably from shot to shot and appear irreproducible.

In apparent contradiction to the rational flux surface argument are the fluctuations observed in the Wendelstein VII-A stellarator, where there is very little shear. However, the high energy electrons produced by ECRF heating in that experiment make higher-order rational flux surfaces more important, if the high energy electrons are constrained to flux surfaces on the ablation timescale. The tumbling pellet argument still holds in shearless plasmas. Would a spherical pellet exhibit fluctuations? Are the fluctuations from highly elongated pellets more pronounced? Do the fluctuations generally get smaller as the mass is eroded and the pellet presumably becomes more spherical? There is probably not much promise in developing more detailed models for this; the net effect of the fluctuations is possibly some small net reduction in the ablation rate. Nonetheless, the fluctuations pose interesting physics questions about the ablation process.

Striations

It is generally observed that visible light from pellet ablation is extended along the magnetic field. Viewed instantaneously, the light is constrained to a long narrow tube. The pitch of the tube has been used in TFR to measure the local components of the magnetic field [10]. Time exposure normal to the pellet path and magnetic field shows very narrow striations aligned with the magnetic field that are apparently correlated with the observed fluctuations in the H_α signal. The ablatant must be ionized very close to the pellet surface to be so well constrained by the magnetic field, or the striations would be washed out. The visible light means that this ablatant plasma must be highly susceptible to recombination followed by immediate re-ionization — it is a cold, dense plasma. This observation is consistent with the addition of a plasma shield to the basic neutral shielding model, and the shield may be further enhanced if the initial neutral ablatant is preferentially emitted along the magnetic field, which follows from non-uniform illumination of the pellet [11, 12]. The implication of these observations, of course, is that the total shield is non-spherical, possibly in both the neutral and plasma shields.

Lack of H_α Fluctuations

After all the attention to H_α fluctuations it must be pointed out that there are instances in which no significant H_α fluctuations exist. These cases may tell us as much about the cause of the fluctuations as anything else if a reasonable physical connection can be made between the observations. Generally, it appears that the lack of H_α fluctuations is associated with the presence of a high-energy electron population, as in the TFR ECRF heating experiments [13], where the ablation rate is extremely high. An explanation of this observation could be that the energetic particles are less constrained to flux surfaces, are not significantly impeded by the neutral and plasma shields, and therefore provide a more uniform illumination of the pellet regardless of plasma geometry and shield details. But how do the observed fluctuations in W VII-A fit into this argument? The implication of a lack of fluctuations is that a hydrodynamic instability is not the sole cause of the fluctuations.

Broad H_α Profiles

The usual observation in ohmic plasmas is that the H_α signal rises more or less continuously (except for fluctuations) until near the end of the pellet life. Often under auxiliary heating conditions, however, the signal rises very rapidly as the pellet enters the plasma and remains nearly constant over much of the pellet lifetime. These atypical H_α signals are usually associated with enhanced ablation effects from neutral beam injection [14] or ECRF heating [13, 15]. Also connected with these enhanced ablation profiles is a lack of mass accountability. These observations can be explained by the influence of nonthermal distributions on the ablation process. The shield, which is largely sustained by the thermal electrons, is relatively weak in the plasma edge. Nonthermal electrons or ions may penetrate the shield and ablate more mass than can be ionized in a compact shield by the thermal electrons. The mass accountability could be associated with a significant neutral and charge-exchange loss of particles not otherwise observed when the shield is compact. The implication of this is that the distribution functions of plasma electrons and ions are important. The compatibility of pellet fueling with various heating schemes needs to be evaluated. It points to the possibility that fast alphas in fusion plasmas could present a problem with enhanced ablation, but if fast alphas are reasonably constrained to their birth surfaces while thermalizing, they may not exist in sufficient quantity to enhance ablation in the outer plasma where the pellets are most vulnerable [16].

T_e Profile Response During Ablation

One final observation that seems to defy adequate explanation is that in some instances ECE signals indicate a precooling of the electrons significantly ahead of the pellet during the ablation process. This was noted in Alcator-C, TFR, and ASDEX experiments where a drop in $T_e(0)$ appeared soon after the pellet entered the plasma but significantly before it reached the axis. In JET the precooling on axis did not appear until the pellet penetrated beyond the $q = 1$ surface. Neutrals from the pellet could penetrate to the plasma center on this time scale, but they would affect the ions — the electrons would see this cooling on a τ_{ei} time scale, which is too long to explain the observation. Another possible explanation is that a macroscopic transport process is induced by addition of the pellet mass to the plasma. It might be expected that a major loss of energy from the plasma would be involved — something that is not observed. Somehow, then, the effect is contained within the plasma, as a sawtooth or other internal disruption (i.e., not extended to the limiter or walls), but apparently affecting only the electron temperature profile and not the density profile.

ABLATION MODEL DEVELOPMENT

What do these observations mean in terms of ablation model and code development? What are the key elements that need to be included for a more complete picture of the ablation process? The elements of a complete model include starting with the basic neutral gas shielding model, because of its general success in both qualitative and quantitative agreement with observed ablation rates.

The energy distribution of electrons and fast ions incident on the pellets must also be included. Approximating thermal electrons as monoenergetic is generally not adequate for plasma temperatures above a few hundred eV [16]. Detailed treatment of the atomic physics of the cloud is required, including all neutral and ionization states, to make quantitative contact with H_α measurements and improve the hydrodynamic calculations in the cloud [17]. Non-thermal electron distributions from ECRF and LH heating schemes and from runaway electrons have been shown to be important, but quantified comparison with experimental results is very difficult because of inadequate knowledge of the distribution function. Qualitative agreement is possible [13]. Fast-ion-enhanced ablation from neutral beam injection can be evaluated quantitatively because of better knowledge of the energy distribution of these ions [14].

Both conduction and convection of energy through the shield need to be evaluated for detailed assessment of the cloud features and shielding effectiveness [17]. This generally tends to require a kinetic treatment of beginning far from the pellet with a Maxwellian distribution of electrons, moving through the outer portions of the cloud where mixing of the cold and hot electrons occurs and the total electron distribution is non-Maxwellian (the collision mean free path of the most energetic electrons is longer than the gradient scale length), and continuing into the very dense cold cloud where a cold electron fluid can be considered. This is a very complex kinetic problem that has only been solved with limiting approximations to conductive and convective flow of energy.

Asymmetry in the ablation parallel and perpendicular to the magnetic field is important. It may elongate the neutral shield in the direction of the magnetic field [11, 12]. Perhaps this implies that a cylindrical model should be considered for the neutral shield as well as for the plasma shield [9] — rather than using a spherical approximation for the neutral shield with a correction for the exposed surface area. A cylindrical model would simplify hydrodynamic calculations by removing the singularity at the critical radius and give some insight into various physical processes of both the neutral gas cloud and the plasma shield.

A possible additional shielding effect that has not received much attention is magnetic shielding. The large amount of energy that the electrons deposit in the vicinity of the pellet leads to a low-temperature, high-density plasma cloud. In higher-temperature plasmas, the kinetic pressure in this cloud may expand the magnetic field around the pellet and reduce the incident flux by reducing the upstream cross-section of the plasma tube that maps onto the pellet and its cloud [9].

The geometric reduction of plasma near the magnetic axis is significant, but perhaps not that important in assessing details of pellet requirements; if the pellets reach the magnetic axis, the major problems of pellet penetration have already been overcome. The reduction in ablation at the axis is an interesting one from a physics standpoint, however.

Perturbations to the background plasma that occur on the ablation time scale should be addressed. Local self-limiting ablation has been modeled by considering various collision and mixing time scales of the plasma electrons [16]. Generally, in larger, hotter plasmas this tends to be less important. In smaller experiments where the plasmas are more collisional, propagation of the ablatant mass around the torus and mixing with the hot plasma may need to be considered. This appears to be particularly important in ZT-40M [7].

Another type of perturbation to the background plasma is nonlocal deposition of the pellet mass over the ablation zone. Generally, models that evaluate the ablation locally use strictly local deposition. In large, hot plasmas, where the scale of the ablation zone is very small compared to the plasma dimension, local deposition is appropriate. But what about global perturbations to the plasma, separate from deposition, as indicated by the ECE measurements showing a T_e response far ahead of the pellet?

The effect of fluctuations in the ablation process as evidenced by the H_α signals may have to be included in some general way if they significantly alter net ablation rate. To be able to model this in detail may be more difficult than can be justified. As stated earlier, it is an interesting physics problem.

Many of these effects have been included in various extensions of the neutral shielding model. Most of them have not been included in any single computational model. Future development will generally concentrate on bringing the various pieces together in more comprehensive, complete models. To guide this effort and to highlight the most important features of these models, further analysis of experimental ablation data is indicated.

ABLATION DATA ANALYSIS

From the physics included in basic ablation models we need to develop scaling laws for pellet ablation and penetration and suggest tests against experimental data. Are there key features of the physics of ablation that change, for example, the scaling of penetration with velocity and pellet size? Are there other relatively simple experimental tests of the basic elements of a given theory that can be proposed?

Detailed comparisons with experimental data are needed. It has been shown that many cases are needed to develop a statistical analysis because of scatter associated with the absolute measurement and penetration depths [11]. Similar uncertainties exist in the pellet mass measurements and plasma properties. We should not only compare the penetration depths with experimental results, but also try to determine whether the shapes of the deposition profiles are in agreement with experimental results.

Tests of ablation and penetration scaling should be done under controlled conditions. Only plasmas with thermal electron distributions and no notable fast ion effects from neutral beam injection or ICRF should be included in analysis of the basic electron ablation. Auxiliary heating conditions must be considered in extending the temperature range of the data, but the results should not be clouded with the effects of non-Maxwellian distributions. Fast ion effects from neutral beam injection in TFTR dramatically change the H_α trace [14]; changes in the H_α signal may then be used as an indication of fast ion effects. No such fast ion effects have been noted in JET ICRF or neutral-beam-heated plasmas [11]. Separate analysis of the effects of runaway electrons and ECH heating is needed. Also, cases with large anomalies due to plasma singularities, e.g., pellets that penetrate too near the magnetic axis, need to be analyzed separately. Most simple scaling arguments break down close to the magnetic axis because geometric effects and lack of approximate linear rise of the temperature profiles.

Cases with very large dips in the H_α signal (presumably from very low order rational surfaces or islands) and cases that produce snakes (crossing the $q = 1$ surface) likely indicate geometric restrictions in the plasma. The JET results show a high correlation between the presence of these large dips in the H_α signal and deeper pellet penetration than in similar cases with more normal signals.

Applying these constraints, we can use statistical analysis of pellet injection data to address the following relationships that arise in evaluating ablation models. The diagnostics required are generally available: a wide-angle H_α monitor, a time-of-flight determination of v_p, a relative mass measurement of individual pellets with a microwave cavity, penetration depth determined from time of flight or soft X-rays, and plasma electron temperature and density profiles.

H_α and $\dot{N}$

One question of long standing is how are H_α and the pellet erosion rate $\dot{N}$ related? We assume that they are linearly related at all temperatures and plasma densities so that the shape of the H_α trace indicates the fueling profile and can be compared with calculated ablation rates. The total integral of the H_α signal plotted versus pellet mass for various pellet sizes, velocities, and experimental conditions should exhibit a linear relationship with small scatter.

Penetration and r_p

How does penetration depth scale with pellet size? A wide selection of pellet sizes is available on the JET injector. The ASDEX centrifuge can generate various pellet sizes. Natural variation in pellet sizes also occurs. Individual mass measurement of each pellet is required. A velocity window could be selected to remove any velocity variations. Controlled plasma conditions are needed to remove temperature and density effects.

Penetration and v_p

How does penetration depth scale with pellet velocity? This question arises in assessing the differences in scaling between a neutral shield and a plasma shield. A scan of lower pellet velocities with present injectors under controlled plasma target conditions should be possible. Velocity and mass measurements are needed for each pellet. The mass measurement removes any clouding of the results by a correlation between pellet size and velocity. The plasma has to be under fairly controlled target conditions so that plasma temperature and density effects can be removed. Another alternative is to probe the plasma with higher velocity test pellets. This high-velocity pellet program is planned, but more immediate experiments can be done at lower velocity.

Penetration and B

Another question that has not been addressed is how penetration depth scales with the magnetic field. The idea here is to see if magnetic shielding is playing a role. Controlled experiments with the magnetic field as an independent parameter while everything else is constant are not done very easily, but perhaps something could be tried to see if any interesting information is gained. Temperature, velocity and size effects need to be eliminated. Statistical analysis could be a means of systematically eliminating the other effects in the same way that global confinement is analyzed.

$\dot{N}$ and r_p

How does the local ablation rate vary with the pellet size? Klaus Büchl has made some observations on ASDEX that show the initial rise of the H_α signal to be independent of pellet size in identical plasma discharges. Is this a general phenomenon? If so, it may indicate that the ablation is restricted by a mass erosion rate — that $\dot{N}$ is independent of r_p — a result contrary to our present ablation models that show $\dot{N} \propto r_p$. (This presumes a linear relationship between H_α and the ablation rate.) Another possibility is that a finite time is required to establish quasi-equilibrium in the pellet cloud and that our hydrodynamic equilibrium models are not applicable in the plasma edge. Individual mass and velocity measurements on pellets of different sizes under controlled plasma conditions are required. A detailed comparison of the initial rise of the H_α traces should be sufficient to answer this question, once the above constraints are met.

SUMMARY

Much physical insight into the rich detail of pellet ablation physics has been gained over the past decade. Understanding the complexity of the large local perturbations introduced by pellets requires insight into a wide variety of plasma physics issues. Progress has been made in the development of computational models that include much of the observed detail. More guidance from analysis is needed, however, to gather the most important pieces of the puzzle together and solidify the projections of pellet needs for future large, hot plasmas.

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