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Results of Hydrogen Pellet Injection into ISX-B

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: ~~A05~~ Microfiche A01

A04

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Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

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Date Published: September 1980

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ABSTRACT

High speed pellet fueling experiments have been performed on the ISX-B device in a new regime characterized by large global density rise in both ohmic and neutral beam heated discharges. Hydrogen pellets of 1 mm in diameter were injected in the plasma midplane at velocities exceeding 1 km/s. In low temperature ohmic discharges, pellets penetrate beyond the magnetic axis, and in such cases a sharp decrease in ablation is observed as the pellet passes the plasma center. This behavior can be accounted for by an ablation model that includes dynamic cooling of the target plasma while the ablation proceeds. Complete penetration can be prevented by operation in low density regimes where runaway electrons are thought to be responsible for high ablation. A similar effect is observed with moderate to large amounts of neutral beam injection. There is a strong enhancement of the ablation rate in the outer 10-cm plasma region even for short heating intervals, which can be explained by the presence of multi-kilo-electron volt ions in the discharge.

Density increases of $\sim 300\%$ have been observed without degrading plasma stability or confinement. Energy confinement time increases in agreement with the empirical scaling $\tau_E \sim n_e$ and central ion temperature increases as a result of improved ion-electron coupling. Laser-Thomson scattering and radiometer measurements indicate that the pellet interaction with the plasma is adiabatic. The low level of power emission from the pellet-plasma interaction region is consistent with negligible charge exchange losses; within the experimental accuracy, nearly all of the pellet mass can be accounted for in the initial plasma density rise. Penetration to $r/a \sim 0.15$ is optimal, in which case large amplitude sawtooth oscillations are observed and the density remains elevated. Gross plasma stability is dependent roughly on the amount of pellet penetration and can be correlated with the expected temporal evolution of the current density profile.

1. INTRODUCTION

The technique of injecting millimeter-size frozen pellets of the hydrogen isotopes at high speed is being pursued as a method for refueling proposed magnetic fusion power reactors. This technique offers a potentially attractive solution to the problem of depositing fuel deeply within the magnetically confined plasma with minimal energy requirements. The problem of pellet ablation and penetration in the fusion plasma environment has been addressed theoretically by a number of workers [1-11], and recent calculations have been performed to investigate the effects of particle and energy transport in pellet injection fueling scenarios [12-16].

Some pellet injection experiments have been performed [17-20], and these, for the most part, have addressed pellet penetration and ablation in the low plasma temperature regime. The limited information available from previous experiments suggests the existence of a neutral gas shielding mechanism of the type described in Refs. [4-7]. The results reported here are also consistent with pellet ablation theories that incorporate neutral gas shielding.

The ISX-B pellet injection experiments are a continuation of those begun of the ISX-A device [20]. Pellet size and velocity have been increased to 1 mm and 1000 m/s, respectively. The improved pellet parameters provide the flexibility to study pellet fueling in the regime of large pellet-to-plasma particle ratio and pellet penetration up to and beyond the plasma center. The topics discussed herein include pellet ablation and penetration in ohmic and neutral beam heated discharges, plasma stability and dynamic response, energy and particle confinement, and localized energy losses.

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2. EXPERIMENTAL DESCRIPTION

2.1 Pellet injector

The pellet injector and associated equipment as installed on the ISX-B device are illustrated schematically in Fig. 1. The gun-type pellet injector is a modified version of the device first used on the ISX-A tokamak [20]. A single, 1-mm cylinder of frozen hydrogen is formed within the liquid helium cooled mechanism prior to initiation of the tokamak discharge. Acceleration of the pellet is accomplished pneumatically by pressurized room temperature helium gas admitted to the breech of the gun mechanism by a fast valve. The 10 T- ℓ of helium propellant produced is exhausted into the attached pellet injection line and effectively prevented from entering the tokamak vacuum vessel by volumetric pumping and a series of small aperture constrictions aligned with the pellet trajectory and two fast operating gate valves that close behind the pellet. The measured angular dispersion in pellet trajectory ($\sim 0.2^\circ$) is well within the 0.64° limit imposed by the narrow apertures in the pellet injection line. Additional design details and performance of the pellet injector are discussed elsewhere [21].

Electronic detection of the pellet prior to entering the plasma is accomplished as the pellet interrupts illumination of a pair of photodiodes that are separated by a distance of 1.1 m. A velocimeter records the time of flight and determines the appropriate time to trigger the various diagnostics including a ruby laser holographic interferometer and shadowgraph diagnostic that obtains plasma density profiles of the ablation cloud and silhouettes of partially ablated pellets in situ. Pellet ablation as studied with this technique is the subject of a forthcoming paper.

Pellet mass is monitored periodically by trapping pellets in the volume between the two fast valves and recording the pressure rise resulting from pellet evaporation. The measured mass distribution given in terms of hydrogen atom content is shown in Fig. 2a. Each pellet contains, on the average, $N = (3.7 \pm 0.2) \times 10^{19}$ hydrogen neutrals; this

Fig. 1. Schematic of pellet injector as installed on the ISX-B device. A single, 1-mm frozen hydrogen pellet is formed within the liquid helium cooled pellet injector and expelled by pressurized helium gas at 26 atm. In addition to pellet detecting photodiodes PD1, PD2, and H α power monitor, diagnostics include: (1) radiometer (pyroelectric detector), (2) Thomson scattering, (3) central channel soft x-ray detector, (4) magnetic probe, (5) neutral particle analyzer, (6) 2-mm microwave interferometer, (7) high speed framing camera/still camera, (8) spectrometers, (9) still camera, (10) pellet-view radiometer, (11) limiter, (12) Langmuir probe, (13) 0.4-mm laser interferometer, (14) pellet-view radiometer.

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Fig. 2. Histograms of (a) pellet mass, N (equivalent H content), (b) pellet velocity, U , and (c) total H_α photons, N_{H_α} , emitted from pellet-plasma interaction zone.

figure is quantitatively in agreement with the expected mass of a 1-mm cylinder of solid hydrogen. The measured velocity distribution for the apparatus is given in Fig. 2b.

2.2 Diagnostics

A Balmer-alpha (and Balmer-beta) light monitor that views the pellet-plasma interaction region from behind is used to measure pellet lifetime and, hence, the average ablation (or ionization) rate. In earlier works we have inferred [18,20] the instantaneous value of the ablation rate from the level of H_{α} light emanating from the excited neutrals within the ablation cloud surrounding the pellet. The assumption was made that the number of ionizing collisions produced by plasma electrons incident on the neutral cloud is proportional to the number of inelastic collisions that result in emission of an H_{α} photon. Accordingly, the total number of H_{α} photons emitted during the complete evaporation and eventual ionization of the pellet by the plasma was interpreted as a direct measure of the pellet mass.

The measured distribution of H_{α} photons is given in Fig. 2c. On the average $7.5 \pm 1.7 \times 10^{17}$ photons are emitted during the ablation process, which, when compared to the pellet mass, indicate that ~2% of the neutrals released emit an H_{α} photon before being ionized (H_{β} light is lower by a factor of 5). The significance of this result, as concerns possible inference of ionization or ablation rates, is discussed in Section 3.

In addition to the H_{α} light measurements, photographic studies using still and high speed framing cameras aimed toroidally allow for direct visual observation of the ablation cloud and motion of the pellet across the plasma column. A still camera that views the plasma from above provides similar information in the plasma midplane. A pair of wide angle pyroelectric detectors separated by 90° along a minor circumference (positions 10 and 14 in Fig. 1) view the pellet-plasma interaction region. They monitor radiation and charge exchange energy losses from the plasma column and analogous losses from the pellet moving in the plasma midplane. Additional detectors that are not in direct line

of sight of the pellet-plasma interaction region monitor radiative and charge exchange losses from the plasma alone (location 1 in Fig. 1). No direct measurements of particle charge exchange losses have yet been made.

2.3 Tokamak

The ISX-B device is a modification of ISX-A [22], which includes neutral beams with injected power of up to 1.2 MW (coinjection). Basic machine parameters are $R_0 = 0.92$ m, $a = 0.27$ m, $B_T = 1.0$ -1.8 T, and $I_p = 100$ -200 kA (feedback controlled). In circular discharge configurations, the plasma volume is a nominal 1.3 m³. Consequently, each pellet has the capability of increasing the volume-average plasma density by $\sim 2.8 \times 10^{13}$ /cm³.

Standard plasma diagnostics are employed, and their locations with respect to the pellet injection sector are indicated in Fig. 1. The beam path of one of the two ORNL neutral beam injectors [23] intersects the pellet trajectory.

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3. THE CORRESPONDENCE BETWEEN PELLET MASS AND H_α MEASUREMENTS

At present there exists no precise method with which to measure instantaneous pellet ablation or ionization rates. Jørgensen [17] captured the partially ablated hydrogen pellets that penetrated the Puffatron plasma and was able to determine mean ablation rates by measuring the residual pellet mass. Thomas [24] has recently developed a single exposure shadowgraph technique that obtains silhouettes of pellets in ISX-B. It is expected that this technique will ultimately provide cross-section information of partially ablated pellets at varying radial positions from which ablation profiles may be inferred.

As noted earlier, we utilized the H_α light emission data in previous experiments to infer instantaneous pellet ionization rates by assuming that ionization of the neutrals (molecular and dissociated hydrogen) within the ablation cloud is by direct impact with plasma electrons. According to this assumption the volumetric ionization rate dn/dt at any given location within the ablation cloud can be written as

$$\frac{dn}{dt} = \overbrace{n_{H_2} n_e \langle \sigma v_e \rangle}^A + \overbrace{n_H n_e \langle \sigma v_e \rangle}^B \quad (1)$$

$$e + H_2 \rightarrow H_2^+ + 2e \qquad e + H \rightarrow H^+ + 2e$$

The simultaneous rate of production of H_α photons by dissociative excitation of H_2 and excitation of H by electron impact is likewise given by

$$\frac{dn_{H_\alpha}}{dt} = \overbrace{n_{H_2} n_e \langle \sigma v_e \rangle}^C + \overbrace{n_H n_e \langle \sigma v_e \rangle}^D \quad (2)$$

$$e + H_2 \rightarrow H + H^* + e \qquad e + H \rightarrow H^* + e$$

The ratios C to A and D to B are approximately constant over the electron energy range of 50 eV to 1 keV and attain asymptotic values of 0.007 and 0.04, respectively. If the ratio of the concentrations of the neutral species in the cloud did not vary, or alternatively, if one of the species were dominant, this result would allow a direct correspondence between the global rates of H_{α} production and ionizations irrespective of the pellet position in the plasma or electron energy within the cloud (except energies sufficiently close to the thresholds for the various processes, viz., ~ 30 eV). From the pellet mass and H_{α} histograms of Fig. 2, we obtain empirically the result $N_{H_{\alpha}}/N \approx 0.02$, which is within the range of cross-section ratios cited above. Accordingly, we offer without further justification the following semiempirical expression to relate H_{α} power, $P_{H_{\alpha}}$, to the local ionization rate, dN/dt ,

$$\frac{dN}{dt} = P_{H_{\alpha}} \times (1.89 \text{ eV} \times e \times 0.02)^{-1} = 1.65 \times 10^{20} P_{H_{\alpha}} \text{ (s}^{-1}\text{)}. \quad (3)$$

From Fig. 2 we note that the distribution of the H_{α} light measurement is considerably broader than the pellet mass distribution. The former was obtained over a wide spectrum of plasma conditions, and the data spread is probably indicative of a departure from the 0.02 proportionality constant due to the different plasma regimes encountered by the pellet. Owing to the uncertainties involved in deriving this result, we hesitate to endorse it as a precise definition of the ionization rate; nevertheless, we shall rely on Eq. (3) in the following discussions in order to interpret the experimental data.

4. GENERAL OBSERVATIONS

4.1 Penetration in ohmic discharges

Typical results of H_α light measurements are shown in Figs 3-6 for ohmic and neutral beam heated discharges; the four examples chosen illustrate the extremes observed in pellet ablation and penetration (or, alternatively pellet lifetime). Intermediate cases have also been studied.

The signature of the H_α signal for the high central electron temperature ohmic case of Fig. 3 is qualitatively similar to that observed on ORMAK and ISX-A. In the initial ~ 10 cm of plasma the ablation is small. Shadowgraphs of pellets taken in this region show that they retain their initial cylindrical shape [24]. The signal increases rapidly as the pellet enters progressively hotter and higher density plasma and decreases abruptly during the final stage of evaporation. The absolute penetration for this example is approximately twice as large as observed in ISX-A (22 cm as compared with 12 cm), which is due for the most part to larger pellet mass (greater by a factor of 6) and higher velocity (a factor of 3 larger). The pellet lifetime, τ , as measured by the duration of the H_α signal, however, is shorter for the present experiment (250 μ s as compared with 350 μ s). This is due to the fact that the higher speed pellets pass quickly through the cooler outer plasma regions and encounter the hotter more dense central core where ablation, or ionization, rates are highest. For conditions with plasma temperature and density increasing along the pellet flight path, the lifetime is not independent of velocity as it would be for a uniform plasma. Finally, for this example, we obtain for the mean ionization rate, N/τ , a value of 1.5×10^{23} ions/s (assuming a nominal size pellet, i.e., $N = 3.7 \times 10^{19}$ H). In comparison to earlier tokamak experiments, this is approximately an order of magnitude greater than the ISX-A [20] and Pulsator [19] results and about four orders of magnitude greater than values reported by Foster et al. [18] for the initial injection experiments on ORMAK. This progression is attributable to the use of larger, higher velocity pellets that penetrate further to encounter the hotter plasma environment.

Fig. 3. Typical H_α light intensity profiles in ohmically heated discharges as a function of inferred penetration into the plasma column. The outer limiter is arbitrarily chosen at the origin. A nominal 27-cm plasma minor radius is assumed. $I_p = 120$ kA, $B_T = 1.14$ T.

Fig. 4. Time exposure photograph showing trail of luminous gas left in the wake of a pellet as it traverses the entire plasma column from left to right and impacts the vacuum chamber wall. The vertical luminous area to the left is the plasma interacting with the material limiter. The photograph was taken from location 7 in Fig. 1.

Fig. 5. Effect of neutral beam injection on ablation profiles showing reduced penetration and broadened H_α profile. Pellet injection occurs 50 ms after the beginning of the 100-ms beam pulse (500 kW, 40 keV, $H^0 \rightarrow D^+$). $I_p = 110$ kA, $B_T = 1.15$ T, $\bar{n}_e = 1.5 \times 10^{13}$ cm $^{-3}$, $T_e(0)$ (during injection) = 1.1 keV.

Fig. 6. Effect of the short duration neutral beam pulse (375 kW, 40 keV, $\text{H}^0 \rightarrow \text{D}^+$) on pellet ablation profile. Pellet injection occurs 3 ms after initiation of the beam pulse. $I_p = 90 \text{ kA}$, $B_T = 1.13 \text{ T}$, $\bar{n}_e = 1.5 \times 10^{13} \text{ cm}^{-3}$, $T_e(0) = 500 \text{ eV}$.

In contrast to previous experience, we have observed ablation profiles of a type illustrated by the lower central electron temperature example of Fig. 3. Because of the reduced temperature and density, the pellet penetrates the entire plasma column (nominally 54 cm plus the additional distance beyond the material limiter) and impacts the inner wall of the vacuum vessel. The large increase in signal beginning at 0.7 ms represents evaporation of the residual pellet mass and rapid recycling of the neutrals from the wall. An important characteristic of the H_{α} signature for pellets that penetrate beyond the magnetic axis is the abrupt decrease in signal as the pellet passes the plasma center and only a gradual and small subsequent recovery. This behavior, which is also evident in Fig. 4, is a manifestation of plasma confinement on magnetic flux surfaces in toroidal geometry. As the pellet progresses toward the magnetic axis, it encounters plasma confined to magnetic surfaces encompassing successively smaller volumes. The heat content, as represented by the plasma contained within nested toroidal flux shells, diminishes and becomes vanishingly small at the plasma center. Inasmuch as the pellet represents a moving source of cold plasma deposited locally and confined on flux surfaces, background electrons whose drift orbits intercept the pellet must provide the ionization energy plus whatever additional heat is transferred to the evolving cold electron population through elastic collisions. It follows that there must be some cooling of the plasma while the ablation proceeds and that the ionization of the pellet is limited by this interaction at radii near the magnetic axis where the plasma volume is smallest and the hot plasma electrons are strongly diluted by large numbers of cold electrons being deposited. We emphasize that this behavior is characteristic of large pellets, viz., those whose mass is comparable to or greater than the total plasma ion content. Nevertheless, this effect should be present for any pellet that reaches the innermost plasma flux surfaces with a nonnegligible mass.

The reduced ablation of the pellet beyond the plasma center is also consistent with this interpretation. Because of the rotational transform, electrons that are cooled by the ablation products as the pellet passes

a given flux surface in the outer half of the plasma will intercept the pellet a second time as it traverses the same magnetic flux surface on the inner half. Accordingly, the ionization rate should be lower, particularly at small plasma radii where the dilution effect is most pronounced. The degree to which the ablation signal is asymmetric about the magnetic axis and the relative amount of pellet mass that impacts the vacuum vessel wall are also explainable in this context as demonstrated by the ohmic examples of Figs 5 and 6.

Implicit in the above remarks is the assumption that the instantaneous position of the pellet within the discharge is given by the product of the velocity measured before the pellet enters the plasma and the running time of the H_α signal. This assumes that the pellet does not experience a significant change in transverse velocity while in the plasma. There is no direct evidence to suggest otherwise since the pellet appears to arrive at the approximate locations of the plasma center and inside limiter on schedule.

The pellet does deviate somewhat from its initial linear trajectory, as illustrated by the slight downward curvature of the ablation cloud in Fig. 4. An additional deflection is observed toroidally in the direction of the electron drift velocity (clockwise in Fig. 1) during the final few centimeters of travel for short-lived pellets. This effect was observed on ORMAK and ISX-A and has been attributed to an imbalance in ablation pressure arising from a slight differential heat flux across the pellet surface [18]. These drifts have little significance concerning the ablation rate or pellet penetration since the transverse motion does not appear to be affected.

4.2 Penetration in neutral beam heated discharges

Experiments performed on neutral beam heated plasmas characterized by large amounts of injected power in comparison to the ohmic power indicate both qualitative and quantitative differences in pellet ablation as compared with the ohmic heating results. With neutral injection the H_α signal is typically much larger in the plasma edge region (the first 10-15 cm), and penetration is substantially reduced, as demonstrated by

the examples in Figs 5-6. Part of the disparity between the two cases in Fig. 5 can be attributed to plasma heating during the 500-kW neutral beam pulse that was initiated 50 ms prior to pellet injection. However, penetration is observed to be larger in ohmic discharges with comparable plasma parameters. This suggests the possibility that the fast ion component contributes to the ablation. Additional support for this interpretation is given by the examples in Fig. 6. In the baseline ohmic discharge [$T_e(0) = 500$ eV], the pellet impacts the inner wall with little ablation occurring in the plasma. A dramatic increase in signal is observed in the outer region of the discharge, and penetration is substantially reduced when pellet injection occurs shortly after the 350-kW neutral beam pulse begins. The electron temperature increase that occurs in the 3-ms heating interval is insufficient to account for the disparity between these examples, particularly in the plasma edge region. However, the fast ion population in the discharge may have had sufficient time to increase to a level at which the heat transport to the pellet is dominated by energetic ions rather than electrons. This is more than likely to be true in the plasma edge where the electrons are cold but not necessarily the case in the hot central region of the discharge where the ablation seems not unlike that observed in the standard ohmic discharges.

An abrupt decrease in the H_α signal is evident at an ~10-cm penetration in the neutral injection example in Fig. 6. This interesting phenomenon occurs to varying degrees but is more pronounced at lower injection power and/or during the initial phase of the neutral beam pulse. It is less apparent for long heating intervals because of increased ablation levels in the plasma interior, as illustrated by the oscillograph in Fig. 7. Moreover, a comparison of Figs 6 and 7 suggests that the influence of neutral injection on the ablation saturates rapidly in the plasma edge region, whereas the contribution from the central plasma region continues to increase for some tens of milliseconds. This is not inconsistent with the manner in which the electron temperature and fast ion density and energy profiles are expected to evolve in the two regions. This topic is addressed more fully in Section 7.3.

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Fig. 7. Effect of high power neutral beam injection (900 kW, 40 keV, $H^{\circ} \rightarrow D^{+}$) on pellet ablation profile and penetration. Pellet injection occurs 40 ms after initiation of the neutral beam pulse. The signal is strongly enhanced in the edge plasma region (plasma radii > 20 cm) as compared with ohmic discharges. The occurrence of high frequency large amplitude oscillations at an 8-cm penetration appears to separate two distinct regions of ablation. $I_p = 125$ kA, $B_T = 1.12$ T, $\bar{n}_e = 4 \times 10^{13} \text{ cm}^{-3}$.

The high frequency fluctuations in the H_α signal that appear in the example in Fig. 7 are observed in both ohmic and neutral beam heated discharges. The amplitude is, in general, proportional to the instantaneous signal level, except in the outer 10-cm region where the fluctuations are suppressed or perhaps obscured by neutral injection. The characteristic scale length is ~ 5 -10 mm, as determined by the radial distance traversed by the pellet between large fluctuations. This structure appears on photographs of the plasma midplane (taken from location 9 in Fig. 1) as an alternating pattern of bright and dark zones (streaks) of red light extending toroidally, which we interpret as indicating the presence, in the ablation products, of molecular ions confined by the toroidal field. These fine scale fluctuations are thought to be due to an ablation instability and not directly related to internal plasma structure (such as rational surface effects).

Finally we note that even at the high injection power level (900 kW) for the example in Fig. 7, pellet penetration is a substantial 20 cm, and the mean ablation rate $N/\tau = 1.9 \times 10^{23}/s$ is only 25% larger than the high temperature and high density ohmic example in Fig. 3.

4.3 Penetration in low density ohmic discharges

Ablation profiles comparable to the high temperature example in Fig. 3 are observed in low density ohmic discharges ($\bar{n}_e \sim 1 \times 10^{13} \text{ cm}^{-3}$) in which significant numbers of runaway electrons are present. The thermal plasma heat flux by itself is insufficient to account for the high ablation, particularly since we observe lower ablation and deeper penetration in runaway free discharges with an equivalent electron temperature [$T_e(0) = 1$ -1.2 keV] but at a higher density ($\bar{n}_e = 1.5 \times 10^{13} \text{ cm}^{-3}$). We attribute this discrepancy to the presence of superthermal or runaway electrons that contribute to the ablation process. Such an interpretation is plausible given that relativistic electrons confined in the plasma have many opportunities to intercept the slowly moving pellet as they circle the torus. Furthermore, the stopping power of the protective ablation cloud for electrons with energies in the many hundreds of kilo-electron volt range is negligibly small, and we would

expect that they impact the pellet surface with little energy loss. From data on the energy loss function for electrons in molecular hydrogen [25], we estimate that a 1-MeV electron will completely penetrate the solid pellet, losing about 5 keV in the process. Less energetic electrons in the 100-keV range will deposit virtually all of their energy deep within the solid interior through multiple ionizations. This ultimately results in volumetric heating and possible expansion of the pellet.

This is an effective and sometimes useful way to prevent pellets from penetrating beyond the magnetic axis in plasmas with insufficient thermal energy content. It is not relevant, however, to pellet injection into plasmas with densities above $\sim 1 \times 10^{13} \text{ cm}^{-3}$, in which case the number of runaway electrons would be greatly reduced [26].

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5. PLASMA RESPONSE IN OHMIC DISCHARGES

5.1 Plasma stability and density behavior

The response of the plasma subsequent to pellet injection depends on the initial discharge conditions and the strength of the cold particle source term locally (the ablation profile). We reemphasize that by virtue of the large mass involved, each pellet has the capability of inducing large and virtually instantaneous perturbations on the local and global plasma parameters of a device the size of ISX-B. If we use the result of Eq. (3) to estimate the strength of the source term at the position of maximum ablation (plasma radius = 7 cm) for the high temperature example in Fig. 3, we obtain for the density increment (averaged over a flux surface)

$$\Delta n_e(r = 7) = \frac{dN}{dt} (4\pi^2 R_o r U)^{-1} = 1.8 \times 10^{14} \text{ cm}^{-3} \quad (4)$$

where the pellet speed U is taken to be $\sim 10^5$ cm/s. This easily exceeds the initial plasma density by a factor of 2, and we anticipate that such a density increase, which is at best adiabatic, would result in a correspondingly large local temperature reduction and a steep gradient at the position of maximum pellet penetration ($r \sim 5$ cm). The perturbations and gradients are more pronounced as the pellet approaches the magnetic axis, although the self-limiting nature of the ablation process discussed in Section 4.1 evidently eliminates the singularity in Eq. (4) at $r = 0$ (viz., $dN/dt \approx 0$ at $r \approx 0$). One could envisage overall two distinctly different situations that represent initial conditions on the evolution of plasma parameters subsequent to pellet injection. In the event that the pellet does not penetrate to the magnetic axis, an inverted density profile will momentarily arise, leaving a core of hot, undisturbed plasma. Because of plasma inductive effects, the current density profile will initially be unchanged but should rapidly evolve to a centrally peaked condition. On the other hand, a pellet that penetrates to the magnetic axis, or just beyond it, should produce a hollow temperature profile initially, which could in turn result in hollow current

density profiles. Apart from localized perturbations in the vicinity of, for example, the $q = 2$ resonant surface, these two situations might give rise to significantly different results as concerns the gross plasma stability.

In this respect minor differences in pellet penetration should be important because of the large pellet mass. This interpretation is suggested by the response of the plasma diagnostics in Fig. 8a to the corresponding ablation profiles of Fig. 8b. As was observed in ISX-A [20], a sharp increase in loop voltage occurs coincident with pellet injection followed by a gradual decay to the preinjection level in ~ 20 ms; the total plasma current is unchanged during the transient. The toroidal electric field increase, which has both resistive and inductive components, is due primarily to increased plasma resistivity resulting from a sudden and large reduction in electron temperature. Radiative power losses as measured by a pyroelectric detector (diagnostic 1 in Fig. 1) exhibit a similar behavior.

The most striking difference in these examples is revealed by the poloidal field magnetic probe measurements ($\dot{B}_\theta$). When the pellet passes just beyond the plasma center, a brief burst of large scale oscillations thought to be $m = 2$ is observed. Owing to the deep penetration, the central electron temperature is reduced sharply, as illustrated by a momentary absence of soft x-ray emissions along the central chord (diagnostic 3 in Fig. 1). The signal recovers gradually and smoothly during the remainder of the discharge, which is notably free of external disruptions.

When the pellet penetrates to within a few centimeters of the plasma center, as in the second example in Fig. 8, we observe a substantial decrease in the amplitude of $\dot{B}_\theta$. The signal level remains suppressed for ~ 30 ms, at which point a "soft" external disruption occurs (current disruptions are not observed). The decrease in x-ray emissions is large but not complete, as in the previous example, indicating that cooling of the inner plasma core is not as severe. The signal recovers rapidly and saturates before the disruption.

Fig. 8. (a) Response of plasma diagnostics to variations in penetration and pellet ablation profiles for low density ohmic discharges.

$I_p = 150$ kA, $B_T = 1.46$ T, $\bar{n}_e = 1 \times 10^{13}$ cm⁻³, $q_a = 3.7$. (b) Ablation profiles corresponding to plasma loop measurements of Fig. 8a. Shortened penetration is thought to be due to the presence of runaway electrons. Plasma minor radius is ~ 27 cm.

The final example in Fig. 8 illustrates the effect of slightly reduced penetration. The MHD level is enhanced strongly, and the instability grows continuously for ~ 30 ms up to the onset of a soft disruption. The initial decrease in soft x-ray signal is not as large as in the previous two examples, and its recovery is more rapid.

This type of behavior is, in general, typical for low density discharges ($\bar{n}_e \approx 1 \times 10^{13} \text{ cm}^{-3}$) where densities subsequent to pellet injection are within the stable operating regime of the relatively low field ISX-B device. It remains true also for higher plasma edge safety factors as illustrated by the examples in Fig. 9, where the plasma current was reduced to 110 kA, resulting in $q_a = 5.2$. Apart from the general characteristics summarized above, there are subtle differences exhibited by these examples, which illustrate the importance of pre-injection plasma conditions and pellet injection parameters. The difference in penetration between shots 15646 and 15674 is thought to be related to the respective level of MHD oscillations prior to pellet injection (compare $\dot{B}_\theta$ signals in the first two oscillograms). Discharges with larger amplitude Mirnov oscillations give rise to lower overall ablation rates, which ultimately extend pellet lifetime and thereby allow penetration to smaller plasma radii. In such cases we observe a prominent double spike feature in the ablation signal that appears at minor plasma radii ≤ 7 cm. This phenomenon is presumably due to internal plasma structure but has not yet been fully explored.

More important differences between these examples, however, are depicted by the magnetic probe and central soft x-ray measurements subsequent to pellet injection. As a result of deep penetration to $r = 0$, a short burst of large amplitude Mirnov oscillations is observed in shot 15674, which is similar to the first example in Fig. 8. When penetration is reduced as in shot 15646, no discernable change in MHD activity is observed, but, in contrast to the previous example, sawtooth oscillations are observed with increasing relaxation time and amplitude for as much as 50 ms following pellet injection. This trend is consistent with a central peaking of the current density profile that would result from preferential cooling of the outer regions of the plasma.

Fig. 9. Oscillographs of central channel soft x-ray emissions and magnetic probe measurements showing detail of plasma response and interrelationship to pellet ablation profiles and absolute penetration. Traces 1 and 2 illustrate discharge characteristics from start to end. Traces 3 and 4 are fast time expansions beginning 6 ms before pellet injection. The high initial level of MHD activity in shot 15674 allows deeper penetration to $r \sim 0$. $I_p = 110$ kA, $B_T = 1.51$ T, $n_e = 1 \times 10^{13}$ cm $^{-3}$, $q_a = 5.2$.

The final example in Fig. 9 differs from the previous two in that the pellet velocity is lower and pellet mass is evidently smaller ($\int P_{H\alpha} dt$ is smaller by a factor of $\sim 2/3$). Both of these factors contribute to reduced penetration. However, the amount of fuel deposited in the outer plasma regions may be somewhat greater than the previous examples since the ablation signal is essentially the same, but, owing to the reduced speed, the pellet residence time is longer. The center of fuel deposition is consequently located at a larger plasma radius, and this ostensibly is the cause of the large, sustained increase in Mirnov oscillations.

These results can be conveniently categorized by a single, semi-empirical parameter that incorporates the strength and shape of the cold particle source term and the local plasma parameters. We define the quantity r_σ to be the radius of the effective parallel electrical conductivity, viz., $r_\sigma = \langle r\sigma_{\parallel} \rangle / \langle \sigma_{\parallel} \rangle$ where the averages are performed over the discharge cross section and $\sigma_{\parallel} \sim T_e^{3/2}$. If the interaction of the cold fuel with the plasma electrons is assumed to be adiabatic, then the local electron temperature following injection, T'_e , can be simply related to the increased density n'_e and the preinjection plasma parameters T_e and n_e by the result $T'_e = T_e n_e / n'_e$ (ionization energy has been neglected). The quantity $\Delta r_\sigma = r'_\sigma - r_\sigma$ would represent the displacement of the "effective" plasma current from its stationary position if the time scale for relaxation of the temperature perturbation subsequent to pellet injection is greater than or comparable to the diffusive time scale for the induced, nonuniform toroidal electric field to equilibrate across the plasma diameter. As such, we cannot identify Δr_σ with the actual displacement in the average location of the plasma current; nevertheless, it should be representative of the direction in which the new equilibrium tends to evolve initially (viz., whether plasma current is forced into or out of the central plasma region).

The results of the Δr_σ calculation for this low density sequence are displayed in Fig. 10, where we have used Eq. (3) to evaluate changes in electrical conductivity from the experimental H_α power profiles. The histograms show a definite trend that is consistent with the intuitive

Fig. 10. Histograms summarizing MHD behavior following pellet injection for low density ohmic discharges ($n_e = 1 \times 10^{13}$, $B_T = 1.51$ T, $I_p = 110$ kA, $q_a = 5.2$). The parameter Δr_σ is defined as $\Delta r_\sigma = r'_\sigma - r_\sigma$ where

$r_\sigma = \int_0^a \sigma(r) r^3 dr / \int_0^a \sigma(r) r^2 dr$ and $\sigma(r) = \sigma(0) [T_e / T_e(0)]^{3/2}$. The prime denotes parameters evaluated immediately following pellet injection, assuming adiabatic dilution [viz., $T'_e(r) = T_e(r) n_e(r) / n'_e(r)$]. Equation (3) is used to estimate n'_e from measured H_α profiles. The measured pre-injection plasma profiles are given by $T_e = T_e(0) [1 - (r/a)^2]^{2.5}$, $n_e = n_e(0) [1 - (r/a)^2]$ where $T_e(0) = 1500$ eV, $n_e(0) = 2.1 \times 10^{13} \text{ cm}^{-3}$.

argument presented above. Large positive values of Δr_0 evidently indicate a broadening (or hollowing) of the current density profile, which is caused by deep pellet penetration. The short burst of Mirnov oscillations that results is not disruptive. For values of Δr_0 centered about the origin (or perhaps displaced slightly negative), we observe either a slight reduction in the MHD amplitude or no discernable change. Increasingly larger negative values of Δr_0 result first in discharges with internal disruptions progressing to those characterized by sustained, high levels of Mirnov oscillations, although the distinction between these two cases is slight in terms of the amount of displacement in r_0 .

The behavior of the line-averaged plasma density following pellet injection differs markedly for these cases, as illustrated by the examples in Fig. 11. The line-averaged densities were obtained from a 2 mm-microwave interferometer and 0.4-mm laser interferometer measurements (locations 6 and 13 in Fig. 1). An initial density increase of $2.6\text{--}3.6 \times 10^{13} \text{ cm}^{-3}$ is observed in a time interval equal to the residence time of the pellet in the discharge ($\sim 300 \text{ } \mu\text{s}$). There is approximately a 100- μs delay before the microwave interferometer responds to the beginning of the ablation pulse, indicating a toroidal transport velocity of $\sim 2 \times 10^6 \text{ cm/s}$ for the fresh fuel (ion thermal speed corresponding to 4 eV). This value is in agreement with all previous measurements of the ablation cloud expansion speed [17,19,20].

Concerning plasma refueling, there is some indication of an optimal penetration depth, as suggested by the density behavior following the initial increment and the respective values of Δr_0 . The density increment appears largest for deeper penetration, but this could be an artifact of the central weighting of the interferometer measurement. Initially, the density decays more rapidly for the central penetration example, which is likely due to profile relaxation effects. The density behavior illustrated by shots 15646 and 15678 is typical for the categories of discharges that exhibit sawtooth oscillations and sustained high levels of Mirnov oscillations, respectively (viz., for pellets that do not penetrate to the magnetic axis). The former is obviously superior in that the density remains elevated until the current ramp-down phase

Fig. 11. Behavior of line-averaged electron density during pellet injection into low target density ohmic discharges. The three cases shown typify results obtained for ablation profiles and corresponding MHD signatures of the types illustrated in Fig. 10. Plasma current ramp-down begins at 150 ms, and the discharge terminates at 200 ms. A steady gas feed rate of 6 T-l/s is required to maintain the target density at $1 \times 10^{13} \text{ cm}^{-3}$. The density increase is completed in $\sim 300 \text{ } \mu\text{s}$.

at 150 ms. For all three examples, however, a characteristic density decay time of at least 50 ms is observed. This is considerably larger than the "effective particle confinement time" of 18 ms inferred from the density and gas feed rate before pellet injection and reflects the fundamental difference between edge and central fueling.

The emphasis in the preceding discussion has been on low density plasmas for the following reasons. First, it is difficult to obtain complete absorption of the pellet in the plasma column for clean, high density discharges [i.e., low $T_e(0)$]. Under these conditions pellets usually penetrate the entire plasma and impact the liner, which almost always results in disruptions. As mentioned in Section 3.3, it is believed that complete penetration is prevented at low densities by superthermal (or epithermal) electrons, and these are absent in high density regimes. Complete penetration is prevented at high densities only in discharges contaminated with impurities [high Z_{eff} and therefore high $T_e(0)$].

The first example in Fig. 12 is a typical high density case. With $Z_{\text{eff}} = 6$ (operation shortly after vacuum opening), the preinjection plasma parameters are high enough to completely absorb the pellet, but maximum penetration is still considerably beyond the magnetic axis. The sawtooth oscillations that were present before injection are not observed afterwards, and, although the MHD activity does not change initially, a series of external disruptions begins at ~ 10 ms after injection. The density attains a maximum value of $\sim 6 \times 10^{13} \text{ cm}^{-3}$ but decays to the preinjection level in ~ 20 ms as a result of the disruptions.

The second example in Fig. 12 illustrates the importance of initial plasma conditions on ablation and plasma response. Pellet ablation is reduced in the plasma column, and the pellet impacts the liner when the level of MHD activity is abnormally high. As a result of complete penetration, the initial disruption is nearly instantaneous and in extreme cases, it occurs in as little as 200 μs after the pellet passes the plasma center. The sharp increase in ablation at an ~ 11 -cm penetration and the pronounced double spike feature are characteristic of discharges with high levels of Mirnov oscillations. This behavior would appear to indicate low plasma edge temperature and the existence of a

Fig. 12. Ablation profiles and corresponding soft x-ray and magnetic probe oscillograms for high density and high temperature ohmic discharges. The third and fourth traces represent fast time scale expansions beginning 12 ms before pellet injection. The first example is typical of quiet preinjection MHD behavior. The plasma becomes disruptive ~ 10 ms following injection. The second example illustrates the effect of poor initial plasma conditions. Penetration is complete, which results in disruptions within ~ 2 ms. $I_p = 150$ kA, $B_T = 1.53$ T, $\bar{n}_e = 3.5 \times 10^{13} \text{ cm}^{-3}$, $T_e(0) = 1.1$ keV, $q_a = 4$, $Z_{\text{eff}} = 5.7$.

steep temperature gradient at $r \sim 16$ cm. (The $q = 2$ surface is estimated from Thomson scattering measurements to be at $r = 18$ cm for these discharges.)

5.2 Plasma profile evolution and energy confinement measurements

The details of the temporal evolution of electron temperature and density profiles were studied by Thomson scattering in the low density regime discussed in Section 5.1. The Thomson scattering system on ISX-B is capable of making four measurements at a single spatial location during a discharge. Complete profile characterization is obtained by scanning the plasma radius over a sufficient number of tokamak shots. The profiles, so obtained, typify the plasma evolution in response to an average ablation profile, since pellet mass and penetration may vary somewhat during an experimental sequence. The resulting plasma profile measurements are illustrated in Fig. 13, along with a composite ablation profile that was obtained by averaging the H_α power profiles for the experimental sequence and using Eq. (3) to convert to ablation rates. At 1.7 ms following pellet injection, the density is elevated everywhere, but the profile is slightly inverted and the corresponding temperature profile is centrally peaked. Some structure is still apparent at 7.7 ms, but for times > 11 ms the profiles relax to the standard bell shaped distributions shown in the final example at 20 ms. The ~ 10 -ms time scale observed for inward diffusion of the density peak implies a particle diffusion coefficient, $D = \ell^2/4\tau$, of ~ 0.63 cm²/ms given a scale length $\ell \sim 5$ cm.

The Thomson scattering measurements provide quantitative results concerning particle and energy balances as well. The data displayed in Fig. 14, which were obtained from the plasma profiles in Fig. 13, indicate that virtually all of the pellet mass can be accounted for in the initial increase in charged particle content. This is to be compared with an efficiency of only $\sim 30\%$ obtained with the standard gas puffing refueling mechanism on ISX-B. The density remains elevated far above the preinjection level for at least 25 ms although there is a slight decay in the first 5 ms following injection. The marked reduction in

Fig. 13. Plasma density and temperature profiles before and after pellet injection into low density ($n_e = 1 \times 10^{13} \text{ cm}^{-3}$) ohmically heated discharges. The corresponding ion deposition profile was inferred from the average of H_α power measurements during the experimental sequence.

Penetration to the magnetic axis is prevented by runaway electrons. A slight inverted density profile 1.5 ms after pellet injection is a result of incomplete penetration. $I_p = 110 \text{ kA}$, $B_T = 1.51 \text{ T}$, $q_a = 5.2$.

Fig. 14. Summary of laser Thomson scattering and central ion temperature measurements for pellet injection into low density ($\bar{n}_e = 1 \times 10^{13} \text{ cm}^{-3}$) ohmically heated discharges. The inventory of electrons in the discharge is represented by N_e . Ion energy content is estimated by assuming that the ion and electron temperature profiles have similar shapes. Energy containment time increases from 9 ms before pellet injection to ~ 25 ms at $t = 125$ ms. Mean pellet speed = 900 m/s and mean atomic content = 3.2×10^{19} .

Z_{eff} at late times is a consequence of dilution of impurities resulting from the plasma density increase. Values of Z_{eff} at early times are unmeasurable due to an inability to separate the resistive and inductive components from the loop voltage transient. Strong cooling of the discharge is indicated by the sharp decrease in the density-averaged electron temperature, $\langle T_e \rangle$, but this recovers rapidly as a result of the large increase in ohmic heating power. The central ion temperature, $T_i(0)$, as determined by neutral particle charge exchange analysis increases after pellet injection primarily as a result of improvement in electron-ion coupling at a higher density ($\tau_{ei} \sim 2$ ms). A decrease in ion temperature immediately following pellet injection was expected, but this could not be verified because of the difficulties inherent in measuring fast transients at low temperatures by neutral particle analysis. No discernable decrease in the electron energy content, E_e , is observed initially, indicating that the interaction is virtually adiabatic. At 25 ms after pellet injection, the plasma energy content that includes the ion component, E_i , increases by ~ 2 kJ, which is a manifestation of improved energy confinement. The resulting increase in energy containment time from 9 ms to 25 ms is consistent with Alcator empirical scaling, $\tau_E \sim \bar{n}_e$. During the transient the fractional amount of ohmic input power attributable to radiation losses does not differ appreciably from the value that is representative of standard ISX-B ohmically heated discharges ($P_{\text{rad}}/P_{\text{OH}} \sim 0.2$).

5.3 Energy losses during ablation

Fast time scale measurements of the total power emission, including radiative and charge exchange energy losses from the pellet-plasma interaction zone, were made with an uncollimated pyroelectric detector (location 10 in Fig. 1). Background radiation from the plasma volume within the field of view of the device and localized emissions from the pellet as it traverses the plasma column are measured simultaneously. Both of these contributions are present in the top trace of the oscillograph of Fig. 15. For reference, the H_α signal is displayed beneath the radiometer signal. Energy losses during ablation are easily distinguished

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Fig. 15. Fast time scale radiometer measurement showing burst of power emitted from pellet during ablation. The gradual rise in background signal is attributable to nonlocalized radiation from the plasma column and corresponds to the large increase in P_{wall} displayed in the examples of Fig. 8a.

from the background as a large signal burst coincident with the H_{α} signal. Assuming that the source is isotropic, a maximum incremental power of <100 kW is inferred from the measurement. The total energy loss over the lifetime of the pellet amounts to a minimal 20 J, which corresponds to ~ 4 eV for each ion-electron pair added to the plasma. The pyroelectric detector does not distinguish between energy carried by particles (viz., charge exchange neutrals) and radiative losses (e.g., Lyman-alpha emission from the pellet cloud); nevertheless, the value of 4 eV per ion pair would suggest that charge exchange losses from the pellet are negligibly small.

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6. NEUTRAL BEAM HEATED DISCHARGES

The strong instability-related perturbations on plasma parameters resulting from pellet injection into ohmically heated discharges are not observed in discharges in which neutral beam injection power exceeds the level of ohmic power. This is illustrated in Fig. 16, where the response of plasma diagnostics for a 500-kW injection case is compared with the baseline ohmically heated discharge. The pellet ablation and discharge characteristics for the two cases correspond to the examples in Fig. 5. With ohmic heating alone, penetration is complete, resulting in large $m = 2$ oscillations and a disruption. Strong plasma cooling is indicated by the increase in radiative power at the instant of pellet injection and by the nearly total decrease in soft x-ray emissions from the plasma center.

With neutral injection, pellet penetration is reduced to ~ 25 cm, and the effect on the discharge is considerably less pronounced. Penetration does not differ substantially from the ohmic examples in Figs 8 and 9, yet the radiative power increase and soft x-ray signal decrease are not as large and recovery is more rapid. The level of B_θ oscillations decreases slightly, and strong $m = 1$ oscillations are observed on the soft x-ray signal (similar to the 22-cm penetration case for the ohmic examples in Fig. 9). Furthermore, large loop-voltage increases, which accompany pellet injection in ohmically heated plasmas, are not observed.

These observations suggest that the initial electron temperature decrease is less pronounced and that recovery is more rapid. The latter could be explained satisfactorily by arguing that the total heating power is large. The fact that the electron temperature decrease initially appears to be small could be explained by the presence of fast ions in the discharge. At low plasma densities, the total energy content in the circulating fast ion component is estimated to be comparable to the plasma thermal energy. The sudden addition of large numbers of cold electrons tends to thermalize these fast ions by the classical slowing-down process. The average slowing-down time, τ_s , for the low density discharge is typically 30 ms, and if the density is increased by a factor of 2 to 3 with a corresponding temperature reduction, τ_s would be

Fig. 16. Comparison of magnetic probe ($\dot{B}_\theta$), radiometer, and central channel soft x-ray measurements for ohmic and neutral beam heated plasmas. Pellet penetration and plasma parameters correspond to the examples in Fig. 5.

reduced to the level of a few milliseconds. The fraction of power transferred to the electrons during slowing-down should also increase as a result of a factor of 2 reduction in the energy, E_c , at which fast ions begin to heat plasma ions preferentially. Both of these factors would contribute to a rapid heating of electrons following pellet injection. This interpretation is consistent with the charge exchange flux measurements displayed in Fig. 17 for the case of hydrogen beam and pellet injection into a deuterium plasma. For hydrogen, the highest energy channels corresponding to the fast ion component are rapidly depleted as a result of pellet injection, whereas the lower energy channels exhibit a sharp increase. A momentary reduction is observed in the deuterium flux at all energies, but at later times the distribution is shifted to higher energies, which is indicative of an increase in ion temperature above the prepellet injection level as demonstrated by Fig. 18. This effect is attributed to the increased plasma density, resulting in improved electron-ion coupling and an increase in the efficiency of neutral beam absorption.

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MEASURED CHARGE EXCHANGE FLUX
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Fig. 17. Deuterium and hydrogen charge exchange flux measurements for pellet injection into a neutral beam heated discharge ($500 \text{ kW } H^0 \rightarrow D^+$). The data correspond to pellet penetration and plasma conditions in Figs 5 and 16.

Fig. 18. Central ion temperature and line-averaged plasma density measurements for hydrogen pellet injection into neutral beam heated deuterium plasma. Plasma conditions and pellet penetration correspond to the data set of Figs 5, 16, and 17.

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7. PELLET ABLATION STUDIES

7.1 Experimental shielding efficiencies

The problem of the ablation of a pellet in a plasma is often formulated in terms of a simple energy balance applied at the receding pellet surface where the incident heat flux is balanced by evaporative cooling of molecular hydrogen. We write the resulting rate equation for generation of equivalent atomic hydrogen in the following generalized form:

$$\frac{dN}{dt} = -8\pi n_s r_p^2 \frac{dr_p}{dt} = \left(\frac{n_e \bar{C}_e}{4} \cdot 2kT_e \right) 4\pi r_p^2 \frac{f}{\lambda} \text{ (atoms/s)} \quad (5)$$

where r_p is the pellet radius, n_s is the solid molecular number density, λ is half the sublimation energy ($\lambda = 0.005$ eV), and $\bar{C}_e = \sqrt{8kT_e/\pi m_e}$ is the electron thermal speed. The quantity in parentheses is the external plasma heat flux, and the parameter f is the factor by which it is reduced at the pellet surface as a result of the thermal resistance of the ablation cloud. The quantity λ/f , which can be thought of as the effective energy that the plasma must supply to liberate a hydrogen atom from the surface, is a measure of the efficiency of the ablation cloud as a thermal barrier.

In principle, values of λ/f could be determined experimentally if the pellet radius and ablation rate were known locally. In the absence of such detailed information, a representative value could be deduced from the measurement of absolute pellet penetration. The indeterminacy in dr_p/dt is conveniently removed by averaging over pellet radius:

$$\left\langle \frac{\lambda}{f} \right\rangle = \frac{\int \lambda/f \, dr_p}{r_p} = \frac{\int_0^\tau n_e \bar{C}_e kT_e \, dt}{4n_s r_p} \quad (6)$$

where τ is the pellet lifetime and the plasma parameters are evaluated along the pellet flight path. For parameters corresponding to the high temperature and density example of Fig. 3, the calculation yields a

value of 2.2 eV for $\langle \lambda/f \rangle$. As seen by the pellet surface, the mean plasma heat flux is reduced by a factor $f \sim 0.0025$ by the ablation cloud. For comparison, shielding factors of 0.25 and 0.015 were observed, respectively, in the early ORMAK [18] and ISX-A [20] experiments. The gradual improvement in shielding is a consequence of the use of progressively larger and higher speed pellets that penetrate more deeply into regions of higher plasma heat flux.

As was pointed out by Rose [1], the intense heat flux of a fusion plasma would likely ionize the expanding gas cloud within a very short distance from the pellet surface (much less than a pellet radius). For these conditions, the ablation problem can be thought of conceptually as one in which ions are liberated from the surface. The parameter λ/f should then be at least comparable to the ionization potential, viz., a few tens of electron volts. Although our results demonstrate less effective shielding than predicted by the so-called ion ablation models, there is a definite trend in the direction of increasing λ/f at higher heat fluxes.

7.2 Comparison with ablation theory

Pellet injection experiments performed to date are too few to adequately determine empirical shielding factors over a broad range of pellet parameters and plasma conditions. In contrast to this situation, the field of pellet ablation theory is rich in the number of diverse models proposed to predict the behavior of a hydrogen pellet immersed in a magnetized plasma [1-11].

The measured values of pellet penetration and ablation rates on ORMAK [18] and ISX-A [20] experiments were in agreement with the neutral gas shielding models of Vaslow [5] and Parks et al. [4]. Although a direct comparison of the present experiment with theory is complicated by the strong pellet-plasma interaction, which effectively prolongs pellet lifetime, fair agreement is still obtained if the perturbative effect of the pellet is included in the ablation rate calculation.

The basic elements of the neutral gas shielding model and recent refinements are described in detail in Refs [4-7]. The model treats the

cloud resulting from surface evaporation of molecular hydrogen as a stopping medium for plasma electrons. Electrons are prevented from impacting the pellet surface at full energy by multiple elastic and inelastic collisions with hydrogen gas in the ablation cloud. The heat flux incident on the exterior of the cloud is taken to be $n_e \bar{C}_e / 4 \cdot 2kT_e$, and the electron motion through the gas is treated as a monoenergetic beam subject to a continuous slowing-down process that degrades the electron energy [4]. Elastic collisions, which are important at low electron energy (viz., ~ 100 eV), further reduce the heat flux by back-scattering and consequent removal of electrons from the incident particle flux. The factor f by which the heat flux is reduced at the pellet surface is determined by solving Eq. (5) along with the following expression that relates the pellet and plasma parameters to the stopping power of the ablation cloud [27]:

$$\frac{dr_p}{dt} = \frac{-0.46}{n_s r_p^{2/3}} \left[\frac{e}{m} n_e \bar{C}_e L(E_e/2) \right]^{1/3} \left\{ \int_{E'}^{E_e} \frac{dE_e}{L(E_e)} + \alpha^{-1} \left[\ln \frac{(\rho + 1) E'}{f E_e} - \rho \right] \right\} \quad (7)$$

where $E_e = 3/2 T_e$ (eV) is the electron energy, m is the molecular mass of hydrogen, and $L(E_e)$ is the stopping cross section (eV $\cdot$ m²) or energy loss function for electrons incident on molecular hydrogen.

The integral represents the distance (in molecules/m²) traveled by electrons in the ablation cloud as they slow down by inelastic collisions only from the initial energy E_e to some intermediate value E' where elastic collisions become important as well. The expression containing the constants α and ρ describes the additional penetration below E' including both elastic and inelastic collisions as energy loss terms for the incident electron stream. Values of the loss function $L(E_e)$ are known [25] in the energy range of interest here. We use the approximate analytic form

$$L(E_e) = \left(2.35 \times 10^{18} + 4 \times 10^{15} E_e + 2 \times 10^{21} E_e^{-2} \right)^{-1} \text{ (eV} \cdot \text{m}^2 \text{)}$$

to fit the data in the interval $0.1 \text{ keV} \leq E_e \leq 10 \text{ keV}$. The energy E' is taken to be 100 eV for which $\rho = 2$ and $\alpha = 1.8 \times 10^{-20} \text{ m}^2$ [28].

Equations (5) and (7) can be solved for pellet radius along the trajectory for prescribed plasma parameter profiles. The solution for steadily rising temperature and density gives monotonically increasing values for the ablation rate. To account for the experimental observation that the ablation rate decreases as the pellet passes the central region of the plasma column, we propose that the plasma is cooled during the ablation process. As a first approximation, a simple one-dimensional thermal equilibrium model is adopted [29]. As the pellet moves between two concentric circular flux surfaces (r_1, r_2) separated in plasma radius by a distance Δr , the temperature of the plasma within is allowed to decrease and equilibrate adiabatically with the cold fuel added. During the time Δt that the pellet resides within this zone, the ablation rate and pellet radius are calculated by solving Eqs (5) and (7) along with the condition that the fuel is added adiabatically in the volume V between the two flux surfaces:

$$\frac{dn_e}{dt} = \frac{1}{V} \frac{dN}{dt} \quad (8)$$

$$\frac{d \ln T_e}{dt} = - \left(1 + \frac{2}{3} \frac{\epsilon_i}{T_e} \right) \frac{d \ln n_e}{dt} \quad (9)$$

$$V = 2\pi^2 (r_1^2 - r_2^2) R_0 \quad (10)$$

$$\Delta t = \Delta r / U = (r_1 - r_2) / U \quad (11)$$

where R_0 is the device major radius and U is the pellet velocity. The ionization energy is ϵ_i ($\sim 15 \text{ eV}$), and its presence in Eq. (9) accounts for the energy that the plasma must expend in ionizing the fuel. The form of Eqs (5) and (7) ensures that the ablation rate will decrease if the electron temperature is reduced in proportion to a corresponding

plasma density increase. The largest temperature reductions occur near the plasma center where V is smallest.

Within the context of this model, the thickness of the zone Δr is of some importance. Strictly speaking, it should at least be comparable to the distance that is traversed by a neutral emitted from the pellet surface before it is ionized and captured by the magnetic field. We estimate this distance to be on the order of 1 cm based on photographs of the luminous ablation cloud. For the plasma to maintain thermal equilibrium locally as stipulated, all hot plasma electrons circling within the toroidal flux shell of thickness Δr must have sufficient time to encounter the cold ablation cloud during the time that the pellet resides in this zone. This is equivalent to the requirement that the pellet transit time be on the order of a few electron toroidal transit times. For pellet speeds $< 10^5$ cm/s and $\Delta r \sim 1$ cm, this condition is fulfilled in the hot central plasma region where self-limiting ablation is important.

A comparison of this model with the experimental ablation profile is given in Fig. 19. The calculation is based on the indicated initial temperature and density profiles that were obtained from laser Thomson scattering measurements prior to pellet injection. Also shown for comparison is the calculated ablation profile (non-self-limiting), which assumes that the plasma parameters are frozen at their preinjection levels. Concerning absolute pellet penetration, agreement with the self-limiting ablation model is good; the general features of the experimental profile are reproduced qualitatively although the experimental profile is more hollow than the calculation. Moreover, the results of the calculation are sensitive to the plasma temperature and density profiles. Within the experimental accuracy of the Thomson scattering temperature measurements alone, the calculated penetration varies between 30 cm and 52 cm (complete penetration).

In general, this type of agreement is obtained in discharge regimes where the line-averaged plasma density exceeds $\sim 1 \times 10^{13}$ cm $^{-3}$. For lower densities, penetration is considerably less than predicted, and this enhancement in ablation is thought to be due to the presence of runaway electrons.

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Fig. 19. Comparison of neutral gas shielding model with experimental pellet ablation profile. The calculations were performed for plasma parameters obtained from Thomson scattering measurements made before pellet injection. The self-limiting calculation allows the plasma temperature to equilibrate with the cold ablation products instantaneously. The non-self-limiting case assumes plasma profiles frozen at their preinjection levels shown above. The calculations were performed at a pellet velocity of 900 m/s and an equivalent spherical pellet diameter of 1.08 mm. The "experimental" ablation rate was obtained by assuming proportionality with the H_{α} signal. $I_p = 150$ kA, $B_{T1} = 1.53$ T, $\bar{n}_e = 3.5 \times 10^{13} \text{ cm}^{-3}$.

7.3 Fast ion enhanced ablation

As noted in Section 4.2, pellet ablation is enhanced during neutral beam injection heating even for short duration neutral beam pulses. This phenomenon is due to the rapid buildup of small numbers of circulating fast ions in the discharge with energies as high as 40 keV. The increased ablation is most pronounced in the edge plasma region where the contribution from cold electrons is small.

Ablation dominated by the ion heat flux was first observed in the Puffatron experiment [17] in which the plasma ions were 20 times more energetic than electrons. Jørgensen [30] recently explained the Puffatron results within the context of the neutral gas shielding model of Vaslow [5]. The results of the present experiment are also consistent with a neutral gas shielding mechanism, although the situation here is more complicated because present pellet ablation models do not allow for two simultaneous (and different) heat flux terms; and, unlike the Puffatron experiments, the electron contribution to the ablation cannot be neglected entirely. Moreover, the distributions of the fast ion parameters across the ISX-B discharge are not known experimentally. Nevertheless, most of the effects observed during neutral injection can be reproduced by comparing the magnitudes of the contribution to the ablation rate from the electron and fast ion components calculated independently. Estimates of the fast ion parameters are obtained from analytic solutions to the time-dependent Fokker-Planck equation.

Equations (5) and (7) can be generalized to account for the effects of fast ions separately by substituting ion properties for electron properties everywhere, viz.,

$$\frac{dN}{dt} = -8\pi n_s r_p^2 \frac{dr_p}{dt} = \left(\frac{n_i \bar{C}_i}{4} \cdot 2kT_i \right) 4\pi r_p^2 \frac{f}{\lambda} \quad (12)$$

and

$$\frac{dr_p}{dt} = \frac{-0.46}{n_s r_p^{2/3}} \left[\frac{e}{m} n_i \bar{C}_i L_i(E_i/2) \right]^{1/3} \int_{fE_i}^{E_i} \frac{dE_i}{L_i(E_i)} \quad (13)$$

where $L_i(E_i)$ is the stopping cross section of the molecular hydrogen cloud for incident protons. Its approximate functional form is given by $L_i(E_i) = 1.93 \times 10^{-20} E_i^{0.4}$ for energies <50 keV [31]. Equation (13) differs from the more complex electron counterpart, Eq. (7), in that backscattering of ions out of the cloud has been neglected, which should result in a slight overestimate of the ablation rate.

The model used to provide the required ion parameters is based on the Fokker-Planck equation describing the slowing-down of ions on the background plasma from their initial injected velocity $V_0 = \sqrt{2m_i E_0}$. Because the ion gyroradius is much larger than the pellet size, the pitch angles of the beam ions are ignored and the isotropized beam slowing-down distribution function is used. For a step function source term S applied at $t = 0$, the solution for the isotropic velocity distribution function, neglecting charge exchange losses and speed diffusion [32], is

$$f(V, t) = S U \left(t - \frac{\tau_s}{3} \ln \frac{V_0^3 + V_c^3}{V^3 + V_c^3} \right) \frac{\tau_s}{4\pi(V^3 + V_c^3)} \quad (14)$$

where U is the step function, $\tau_s = 0.12 (T_e / 1 \text{ keV})^{3/2} / (n_e / 10^{19} \text{ m}^{-3})$ is the Spitzer ion-electron momentum exchange time, and $E_c = m_i V_c^2 / 2 = 14.8 T_e$ is for hydrogen, the energy during the slowing-down process at which energy is transferred equally to plasma ions and electrons. These parameters vary greatly across the discharge as does S . The fast ion density at any position in the plasma is given by the first moment of f ,

$$n_i(\bar{x}) = \int_{V(t)}^{V_0} f(\bar{x}, V) 4\pi V^2 dV \quad (15)$$

where the lower limit varies in time as

$$V(t) = \left[e^{-3t/\tau_s} (V_0^3 + V_c^3) - V_c^3 \right]^{1/3} \quad (16)$$

Accordingly, the distribution function and all relevant moments will attain equilibrium values when $V(t) = 0$, corresponding to $t = \tau_f = \tau_s / 3 \ln(1 + V_o^3/V_c^3)$. In ISX-B, τ_f varies from a few milliseconds in the cold plasma edge region to several tens of milliseconds in the hot plasma center. Consequently, the contribution to the ablation from fast ions should saturate more rapidly in the edge as is observed experimentally.

As far as the ablation calculation is concerned, the energy chosen to be representative of the fast ions is important. Unlike electrons, the energy distribution function is non-Maxwellian and differs in shape with time and position in the plasma owing to wide variations in τ_f . In particular, for a given time t' and a fixed location in the plasma, the ion population above the velocity $V(t')$ will remain constant for $t > t'$, but the distribution below $V(t')$ will continue to evolve up to $t = \tau_f$. Consequently, the average energy calculated from $1/n_i \int m_i V^2/2 f dV$ decreases in time. If this energy were used in Eqs (12)-(13), the calculated ablation rate would also decrease (incorrectly) as time proceeds, even though n_i increases. This is due to the weak dependence on n_i in Eq. (13) [which dominates over Eq. (12) in the dynamics of the ablation process] [4-7]. Using the functional form for $L_i(E_i)$ in Eq. (13), the dependence of the ablation rate on the fast ion parameters is seen to vary as $dr_p/dt \sim n_i^{1/3} E_i^{0.9}$ or $(dr_p/dt)^3 \sim n_i E_i^{2.7}$. The higher energy spectrum of the distribution function is more heavily weighed, and accordingly we choose the following moment as an approximation for the representative energy of the fast ion component:

$$n_i \langle E_i^3 \rangle = \int_{V(t)}^{V_o} (1/2 m_i V^2)^3 f(V) 4\pi V^2 dV \quad (17)$$

and

$$E_1 = \langle E_1^3 \rangle^{1/3}$$

The integrations give

$$n_i \langle E_i^3 \rangle = \frac{S\tau_s}{3} \left\{ \frac{E_o^3 - E(t)^3}{2} + E_c^3 \ln \frac{E_o^{3/2} + E_c^{3/2}}{E(t)^{3/2} + E_c^{3/2}} - E_c^{3/2} [E_o^{3/2} - E(t)^{3/2}] \right\}$$

and

$$n_i = \frac{S\tau_o}{3} \ln \frac{E_o^{3/2} + E_c^{3/2}}{E(t)^{3/2} + E_c^{3/2}}$$

where $E(t) = m_i V(t)^2/2$ for $t < \tau_f$ and $E(t > \tau_f) = 0$.

The model adopted for the fast ion source term is based on the neutral beam deposition calculations of Rome et al. [33]. At any plasma radius the fast ion density input rate is determined by the neutral beam current I_o and the spatial shape factor $H(r)$ as

$$S(r) = \frac{I_o/e}{(2\pi R_o)(\pi a^2)} H(r) \quad (18)$$

where $1/\pi a^2 \int_0^a 2\pi r H(r) dr$ represents the fractional beam current absorbed and confined as fast ions (typically 0.6-0.7 for low density ISX-B operation). The form of $H(r)$ is dependent on neutral beam energy and the electron density profile, but it is always centrally peaked for ISX-B injection conditions and is approximately triangular for parabolic density profiles. The ablation calculation is relatively insensitive to variations in $H(r)$ because of the weak dependence in Eq. (13) on n_i .

A comparison of the separate ablation rates calculated for electrons [Eqs (5) and (7)] with that of fast ions [Eqs (12)-(13)] is presented in Fig. 20 for the conditions representing the examples of Figs 5-6. The

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Fig. 20. Ratio of the ablation rate calculated from electrons to that from fast ions for different neutral beam pulse durations and power levels. The various cases correspond to the conditions in Figs 5 and 6. Calculations for the low power examples are based on plasma parameters corresponding to $T_e = 500[1 - (r/a)^2]$, $n_e = 2.3 \times 10^{13}[1 - (r/a)^2]$, $H(r) = 2.5(1 - |r|/a)$. The high power example is based on $T_e = 1150 \times [1 - (r/a)^2]^4$, $n_e = 3.5 \times 10^{13} [1 - (r/a)^2]^3$, $H(r) = 4[1 - (r/a)^2]^6$.

individual ablation rates were calculated at each spatial location for equal pellet radius. The ratios shown are therefore independent of this parameter. The results up to ~5-cm penetration are uncertain because this is the region where charge exchange losses of fast ions with neutrals cannot be neglected; moreover, the edge plasma parameters are not well characterized. Nevertheless, very little ablation occurs in this region, and so the errors are inconsequential. For the 3-ms-heating example corresponding to $T_e(0) = 500$ eV, the fast ion contribution is greater everywhere, but this is most pronounced in the first 10 cm of penetration where $(dN/dt)_i$ is a factor of 5 to 10 larger than $(dN/dt)_e$. In the central region the fast ion contribution is greater only by a factor of 2. These observations are at least in qualitative agreement with the result of Fig. 6, although a direct comparison at the plasma center is not possible because the pellet radius there is obviously different for the two examples. From the form of the ablation equations, a correction for the effects of pellet size reduction in the neutral injection case relative to the ohmic case would increase the ablation rate of the former.

In the second calculation at 375 kW, pellet injection was delayed 50 ms relative to the start of the heating, and in order to study the effect of the fast ion contribution alone, the plasma parameters were artificially held fixed at the levels of the preceding example. There is little difference in the first 10 cm of penetration between the two examples, and even at the plasma center, the ion contribution has increased by only ~30%.

The most important effect of longer beam pulse duration is the resultant plasma heating that increases the contribution from the electrons. This is illustrated by the 500-kW calculation corresponding to the plasma parameters of Fig. 5 that were measured 50 ms after initiation of neutral beam heating but just before pellet injection. The result in the edge plasma region is similar to the previous examples, but in the center the 1.1-keV electrons contribute as much to the ablation as the fast ions, even though the beam power is higher in this case than in the previous examples. In Fig. 21 we compare the experimental ablation profile with numerical solutions of the ablation equations that would

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Fig. 21. Comparison of the experimental ablation profile during neutral beam injection with lower limit (fast ions) and upper limit (fast ions and electrons) ablation calculations. The calculation labeled "electrons and fast ions" assumes that the contributions to the ablation rate that were computed separately are additive. The self-limiting ablation mechanism was not included in the calculations. The plasma parameters and $\Pi(r)$ profile correspond to the high power injection case in Fig. 20.

represent the lower and upper limits on ablation rate and pellet penetration if the self-limiting ablation mechanism described in Section 7.2 were neglected. The curve labeled "ions and electrons" is an approximation obtained by assuming the ablation rate to be equal to the sum of the ion and electron components calculated separately; it is an overestimate of the ablation rate. Similarly, the calculation for ions alone underestimates the ablation rate.

As noted above these calculations do not include the self-limiting ablation effect discussed in the previous section. Although the assumption that the plasma electrons equilibrate with the cold fuel on the ablation time scale is likely a correct one, the same assumption may not be valid for the fast ion component. However, it appears that self-limiting ablation occurs to some extent with neutral beam injection, as illustrated by the decrease in H_{α} signal as the pellet passes the plasma center in Fig. 6. In the central region it is possible that this is accomplished by depletion of the limited number of fast ions by the finite ablation cloud "target." The effect of any interaction of this nature would be most pronounced in the plasma interior where ablation rates would be reduced, resulting in increased penetration; this would improve the agreement in Fig. 21.

Although we can at least explain qualitatively the ablation results in ISX-B within the context of a neutral gas shielding mechanism, considerable experimental and theoretical work remains to be done in the area of pellet-plasma interaction, particularly in the large pellet mass regime. It is also possible that an additional pellet shielding mechanism may be operative (such as magnetic shielding) in the present experiments, but this would most likely be true in the hot central plasma regions where the ablation physics is unfortunately obscured by the interaction of the cold ablation products with the plasma.

8. CONCLUSIONS

We have addressed several related issues concerning the interaction of hydrogen pellets with the tokamak plasma. The use of large pellets, containing more atoms of fuel than ions in the discharge, has made possible deep penetration into the plasma and the study of plasma response in the regime of large density increase. On the whole, the tokamak plasma is surprisingly stable to large and virtually instantaneous changes in local plasma temperature and density. Both energy and particle confinement improve following pellet injection; plasma energy losses during injection are not significant.

The ablation of pellets in the 1-keV electron temperature regime is adequately modeled by neutral gas shielding theories. A significant ablation effect from fast ions has been observed, which also appears to obey a neutral gas shielding law.

No serious problems are foreseen for future continuous fueling operation using pellets of smaller relative mass injected repetitively.

ACKNOWLEDGMENT

The authors wish to acknowledge the many helpful discussions with J. T. Hogan and J. D. Callen.

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