Solid Hydrogen Pellet Injection into the ORMAK Tokamak

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SOLID HYDROGEN PELLET INJECTION INTO THE ORMAK TOKAMAK*

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ABSTRACT

Solid hydrogen spheres were injected into the ORMAK tokamak as a test of pellet refueling for tokamak fusion reactors. Pellets 70 μm and 210 μm in diameter were injected with speeds of 91 m/sec and 100 m/sec, respectively. Each of the 210- μm pellets added about 1% to the number of particles contained in the plasma. Excited neutrals, ablated from these hydrogen spheres, emitted light which was monitored either by a photomultiplier or by a high speed framing camera. From these light signals it was possible to measure pellet lifetimes, ablation rates, and the spatial distribution of hydrogen atoms in the ablation clouds. The average measured lifetime of the 70- μm pellets was 422 μsec , and the 210- μm spheres lasted 880 μsec under bombardment by the plasma. These lifetimes and measured ablation rates are in good agreement with a theoretical model which takes into account shielding of plasma electrons by hydrogen atoms ablated from spherical hydrogen ice.

1. INTRODUCTION

Tokamak plasmas are initially created by electrical breakdown of a gas prefill. At later times the plasma density typically decays¹ as particles are lost to walls and limiters and are not replaced. Several

*Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation and the University of Illinois.

mechanisms for refueling tokamaks have been suggested. Currently, tokamaks are often refueled by puffing gas into the edge of the plasma during the discharge.²⁻⁴ The problem of maintaining plasma density will become more serious as divertors are introduced, as evidenced by experiments with the DITE⁵ bundle divertor. In fusion reactors, refueling will be necessary to sustain the fusion burn.⁶⁻⁷

According to current thinking, gas puffing leads to increases of the density in the center of the plasma by one of two mechanisms, either by transport of energetic charge-exchange neutrals reflected from the vacuum walls⁸ or by the inward force of the Ware pinch.⁹⁻¹⁰ In future fusion power reactors these mechanisms will likely be inadequate: energetic neutral particles will be attenuated before they can reach the plasma center, and the Ware pinch will be weaker in larger, hotter plasmas.

The injection of very high energy neutral particles has also been suggested as a means of refueling tokamak plasmas.¹¹ However, only atoms with energies above 100 keV can penetrate into the interior of large plasmas, and particle replacement by high energy neutral particles leads to prohibitively large densities of stored power.

As an alternative to refueling by cold gas (puffing) or by high energy neutral particles, the injection of macroscopic fuel pellets has been suggested. Fuel pellets ablate as they travel through the plasma due to bombardment by energetic electrons and ions. If the pellets are fast enough and large enough, they will reach the center before being completely expended. This method avoids the problems associated with the other refueling schemes, and as a consequence many tokamak reactor concepts have incorporated this refueling technique into their designs.¹² The problem of how far a pellet penetrates is a complicated theoretical question which must ultimately be tested by experiment. The work described in this paper is a first attempt to determine experimentally the penetration depth of pellets into a tokamak-produced plasma.

The theoretical investigation of pellet ablation was initiated by Spitzer et al. in 1954.¹³ Since then, the problem has been attacked

theoretically by Rose in 1968,¹⁴ Gralnick in 1973,¹⁵ and most recently by Parks et al.¹⁶ Jørgensen et al.¹⁷ have performed experimental studies of the ablation of hydrogen pellets preinjected into a short-lived (4-5 μ sec) rotating ion plasma.

This paper describes the results of two experiments, carried out a year apart, in which solid spherical hydrogen pellets were injected into the ORMAK tokamak.² During the first experiments, 70- μ m pellets were injected at an average speed of 91 m/sec; in the second experiments, 210- μ m pellets were injected with a velocity of 100 m/sec. Using pellets of differing size has provided a two-point check on theoretical calculations, and on this basis we have made an attempt at extrapolating to larger tokamak plasmas.

Section 2 describes the experimental setup: the pellet injector, plasma conditions, and diagnostics. The results of the experiments are presented in Section 3 and compared with a theoretical model in Section 4. Conclusions including extrapolations to larger tokamaks are given in Section 5.

2. DESCRIPTION OF THE EXPERIMENT

A schematic diagram of the experimental setup is shown in Fig. 1. Spherical pellets of solid hydrogen were created by the breakup and subsequent freezing of a jet of liquid hydrogen flowing from a nozzle. The pellet injector is indicated at the bottom of Fig. 1 and has been described in detail elsewhere.¹⁸⁻¹⁹ Pellets of 70- μ m diameter were created at the rate of 1×10^5 /sec, and the 210- μ m pellets were made at the rate of 2.6×10^4 /sec. For injection into ORMAK two valves were opened, as shown in Fig. 1. Pellets were accelerated by a rapid gas dynamic expansion as they passed along a tube connecting the two valves, and during this acceleration some pellets were fragmented by nonuniform pressure forces. In the following discussion, only full-size pellets will be considered. After passing through both valves, the pellets traversed a 300-cm path before reaching the plasma.

Fig. 1. Schematic of the pellet injection apparatus and parts of the ORMAK tokamak relevant to pellet injection experiments. The pellet injector and ORMAK cross section are not to scale. The double valve arrangement shown was used in the 210- μm pellet experiments. A single valve was used to inject 70- μm pellets.

Pellets were injected at 45° to the plasma radius of ORMAK, as indicated in Fig. 1. The plasma radius to the limiter is 23 cm, but some cold plasma exists between the limiter and the wall at 25 cm. Most of the 70- μm pellet experiments were carried out with plasma currents of 120 kA, line average densities of $2.2 \times 10^{13} \text{ cm}^{-3}$, and central electron temperatures of about 900 eV. The 210- μm injection experiments had 60-kA plasma current, average densities of about $1 \times 10^{13} \text{ cm}^{-3}$, and central temperatures of 650 eV.

Each pellet increased the average plasma density by less than 1%, which was below the sensitivity of the microwave interferometer. Thomson scattering was ineffective in the interaction region near the plasma edge, but electron density and temperature just inside the liner were monitored by a double Langmuir probe. Light from excited hydrogen atoms in the ablation cloud provided the principal diagnostic signal for studying details of the plasma-pellet interaction. This light output was monitored by using either a photomultiplier tube (as in Fig. 1) or a high speed framing camera. Light from the ablating cloud was reflected into these devices by a mirror with a hole in its center through which pellets could pass. The phototube was used in conjunction with an H_α interference filter. The camera (Wollensak[†] SF2 FASTAX II) was fitted with a 135-mm lens. The camera speed was 7100 frames/sec during the 210- μm pellet experiments and 14,200 frames/sec for the 70- μm pellet runs.

3. EXPERIMENTAL RESULTS

Detailed data on pellet lifetimes and ablation rates were derived from the photomultiplier and framing camera data. Most of the examples in this section were taken from the 210- μm pellet runs because the larger pellets resulted in better signal-to-noise ratios. Results for the 70- μm pellets were qualitatively similar.

[†]Wollensak Optical Company, Rochester, New York, USA.

It is possible to infer ablation rates directly from photomultiplier signals because the ablation rate is directly related to rate of production of H_{α} photons. This follows from the fact that plasma electrons ionize hydrogen atoms rather rapidly, so that ablation and loss rates are balanced,

$$\frac{dN}{dt} = N_0 n_e \langle \sigma v_e \rangle_{\text{ion.}}$$

where dN/dt is the ablation rate, N_0 is the number of ablated neutrals in the plasma, n_e is the electron plasma density, and $\langle \sigma v_e \rangle_{\text{ion.}}$ is the rate coefficient for ionization of neutrals. The number of H_{α} photons, N_{α} , is equal to the neutral excitation rate of hydrogen atoms,

$$\frac{dN_{\alpha}}{dt} \propto N_0 n_e \langle \sigma v_e \rangle_{\text{exc.}}$$

Combining equations,

$$\frac{dN_{\alpha}}{dt} \propto \frac{dN}{dt} \frac{\langle \sigma v_e \rangle_{\text{exc.}}}{\langle \sigma v_e \rangle_{\text{ion.}}}$$

i.e., the rate of H_{α} photon production is directly proportional to the ablation rate.

A typical H_{α} signal arising from excitation of neutral atoms in the pellet ablation cloud is shown in Fig. 2. The top trace displays the H_{α} signal for a full tokamak discharge. In this trace, the initial light signal peak between 4 and 15 msec was due to light generated during breakdown of the discharge. The pellet injection valves (see Fig. 1) were opened at 20 msec, and some pellet fragments, which were accelerated ahead of the full-size pellet, caused small light bursts between 33 and 50 msec. Light bursts from 210- μm pellets the plasma appeared just after 50 msec. The timing between the opening of the valves and the initial arrival of pellets gives a measure of the pellet velocity. The first two of the full-size pellets are shown on an expanded trace at the bottom of Fig. 2. Fluctuations on the light burst signals are thought to be due to low level MHD instabilities, as similar fluctuations have been observed during gas puffing. The pellet lifetime is determined by measuring the overall duration of a light burst.

Fig. 2. H_{α} light signal output from a photomultiplier tube viewing the plasma along the pellet injection path. The top trace records the entire discharge from the time of gas breakdown at 4 msec until the plasma current is turned off at 64 msec and subsequently decays. The bottom trace is a time expansion of a segment of the top trace, as noted.

Table 1 lists data on the lifetimes of 70- μm and 210- μm diameter pellets for a number of runs. Excluding framing camera data, which contains rather large uncertainties resulting from time between frames, the average lifetime for the 70- μm pellets, traveling at a mean speed of

Table 1. Pellet data

Pellet Diameter (μm)	Pellet Velocity (m/sec)	Plasma Current (kA)	Toroidal Field (kG)	Pellet Lifetime (μs)
70	85	120	18	420
70	90	120	18	400
70	90	120	18	410
70	90	103	16	430
70	90	120	18	450
70	90	120	18	440
70	100	120	18	500
70	90	120	18	490
70	100	120	18	340
70	95	120	18	410
70	85	120	18	360
70	95	120	18	225-375 ^a
70	85	120	18	200-335 ^a
210	100	60	11	780
210	100	60	11	890
210	100	60	11	970
210	100	60	11	840
210	100	60	11	900
210	100	60	11	850
210	100	60	11	920
210	100	60	11	840-1120 ^a

^aData from movie pictures.

91 m/sec, was 422 μ sec. The average lifetime of the 210- μ m pellets was 880 μ sec and their speed was 100 m/sec. The path lengths of these pellets in the plasma were 3.8 and 8.8 cm; and because they were injected at a 45° angle, their radial penetration depths were 2.7 and 6.2 cm.

Figure 3 shows data taken from three different 210- μ m pellet light bursts. By overlapping data points, it is possible to deduce the general ablation rate characteristics of a pellet moving through the plasma.

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Fig. 3. Superposition of H_{α} light signals from three 210- μ m pellet light bursts, as detected by a photomultiplier. The ablation rate was derived by equating the integrated light signal to the pellet mass. The solid curve is the calculated ablation rate (see Section 4).

The ablation started off rather slowly in the tenuous plasma outside the limiter, reached a maximum, and dropped quickly to zero as the last of the pellet was vaporized. From the figure the lifetime is seen to be near the 880- μ sec average obtained from Table 1.

Data from four 70- μ m pellet light bursts are shown in Fig. 4. This data is similar to that of Fig. 3, except that ablation rates are generally much lower and the lifetime is shorter. The lifetime, as measured from the data in Fig. 4, is near to the 422- μ sec average lifetime obtained from Table 1.

Fig. 4. Superposition of H_{α} light signals from four 70- μ m pellet light bursts, as detected by a photomultiplier. The ablation rate was measured as in Fig. 3, and the solid curve was calculated using the theory outlined in Section 4.

A more graphic illustration of the plasma-pellet ablation was obtained from fast framing camera pictures. The film was sensitive only to visible light, and no filters were used. Figure 5 shows a sequence of six frames encompassing the lifetime of one 210- μm pellet. As the pellet entered the plasma, the intensity of the ablation cloud grew. The half width of the largest ablation cloud was 50 times the size of the pellet. In the last frame the pellet was near extinction. As can be seen from a close examination of the last two frames, the pellet path deviated from a straight line near the end of its life. Motion across the plane of the film caused the ablation cloud to have a slightly noncircular appearance in the last frame. Taking into account the optics of the system and a 30° tilt of the camera, the pellet motion curved in the toroidal direction (i.e., along the toroidal magnetic field in ORMAK).

The pellet speed and lifetime can also be determined from the framing camera data by measuring distances on the film and, by knowing the film speed, converting these distances into time. This information is also given in Table 1.

Microdensitometer scans of the ablation cloud are shown in Fig. 6. The data for this figure were taken by scanning the film of Fig. 5 with an 8- μm -wide slit and recording transmitted light. In Fig. 6 the first record of the ablation cloud was assumed to occur one frame (140 μsec) after the pellet entered the tenuous plasma between the wall and the limiter. With this assumption, the lapsed time is in excellent agreement with the average pellet lifetime.

The curvature of the pellet away from its injection path is also illustrated in Fig. 6. This curvature has not yet been fully explained, but preliminary calculations indicate that it may be due to a net reaction force arising from an imbalance in the ablation rate on opposite sides of the pellet.

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Fig. 5. Enlargement of movie film exposed during the lifetime of a 210- μ m pellet. A distance scale is shown for reference. On this scale it has been assumed that the first frame was exposed 140 μ sec after the pellet entered the plasma chamber. A negative of the film is displayed, so that light from the pellet cloud appears as dark circles.

Fig. 6. Microdensitometer scans of the movie film displayed in Fig. 4. The vertical scale gives the ablation cloud brightness, each vertical division representing 4% light transmission through the movie film. The horizontal axis is a scale of distance along the toroidal field showing the size of the ablation cloud. The third axis shows the radial penetration distance of the pellet into the plasma.

4. COMPARISON WITH THEORY

Among the experimental results which were presented in Section 3, the data on the lifetime and ablation rate are subject to direct comparison with approximate theoretical values. The theory to be employed for this comparison is that of an ablating solid hydrogen pellet in a plasma, as developed recently by Parks et al.¹⁶ The essential features of the theoretical model are as follows: neutral molecules evaporate from the pellet as a result of its elevated surface temperature and instantly form a quasi-steady neutral ablation cloud around the pellet. The incident electron energy flux is then shielded by this ablation cloud, with most of the flux going into accelerating and heating the cloud. As a result, only a fraction of the incident electron energy flux reaches the surface of the pellet, raising its surface temperature to a point where the incoming energy is balanced by the energy lost through vaporization. The vaporization rate, in turn, determines the total integrated neutral gas cloud density.

A slightly modified version of the original model is used here. It differs principally in that the hydrodynamic behavior of the ablation cloud is treated in more detail²⁰ and the sonic flow approximation is discarded in favor of self-consistent transonic solutions. Still, the key elements and overall simplicity of the original model are retained. In this model the ablation rate is given in terms of the local values of electron energy, $E_{e\infty}$ (eV), and density, $n_{e\infty}$ (cm^{-3}), by two coupled ordinary differential equations.²⁰ The first equation, which incorporates the concept of a shield, expresses the amount of material that the pellet must supply in order to slow electrons down to an arbitrary energy E_{e_0} before they strike the pellet surface. In terms of the ablation rate, dN/dt , this shielding requirement reduces to

$$\begin{aligned} \frac{dN}{dt} &\equiv 4\pi n_s r_p^2 \frac{dr_p}{dt} \\ &= 5.58 \times 10^{-10} \frac{n_{e\infty}^{1/3}}{M^{1/3}} E_{e\infty}^{1/6} r_p^{4/3} [L(E_{e\infty}/2)]^{1/3} \int_{E_{e_0}}^{E_{e\infty}} \frac{dE_e}{L(E_e)} \end{aligned} \quad (1)$$

where $L(E_e)$ is a function representing the cumulative loss of energy of electrons in molecular hydrogen by inelastic collisions.²¹ $L(E_e)$ is approximated analytically by the expression

$$L(E_e) = \left(2.35 \times 10^{14} + 4 \times 10^{11} E_e + \frac{2 \times 10^{17}}{E_e^2} \right)^{-1} \quad (\text{eV-cm}^2)$$

The second equation is an expression of conservation of energy applied at the surface of the receding pellet whereby the incident energy flux is equated to the rate of cooling by evaporation of molecular hydrogen,

$$\frac{dN}{dt} = 2.16 \times 10^{10} r_p^2 n_{e_\infty} E_{e_\infty}^{1/2} E_{e_0} \quad (2)$$

In the above equations, $\frac{dN}{dt}$ is the ablation rate in atoms per second, n_s is the number density of atoms in the solid, r_p is the instantaneous pellet radius in centimeters, M is the molecular weight of the fuel, and E_{e_0} is the energy (in eV) with which electrons strike the pellet surface. The latter is usually much smaller than the energy of the electrons external to the shielding gas cloud, E_{e_∞} . Together, these equations completely determine the temporal behavior of the pellet radius (and therefore the ablation rate) for any prescribed values of electron temperature and density and initial pellet size. In particular, direct comparison with experimental observation follows from knowledge of the pellet speed and trajectory and given tokamak plasma conditions.

Numerical solutions were obtained for the approximate conditions under which the 210- μm experiments were performed using the following spatial temperature and density profiles:

$$\left. \begin{aligned} T_{e_\infty} \text{ (eV)} &= 125 [1 - (r/25)] \\ n_{e_\infty} &= 25 \times 10^{11} [1 - (r/25)] \end{aligned} \right\} \begin{aligned} &23 \text{ cm} \leq r \leq 25 \text{ cm} \\ &\text{(between limiter edge and liner)} \end{aligned}$$

$$\left. \begin{aligned} T_{e_\infty} \text{ (eV)} &= 10 + 513 [1 - (r/23)] \\ n_{e_\infty} &= 2 \times 10^{11} + 1.75 \times 10^{13} [1 - (r/23)^2]^{1.5} \end{aligned} \right\} \begin{aligned} &15.6 \text{ cm} \leq r \leq 23 \text{ cm} \\ &\text{(within discharge)} \end{aligned}$$

where r is the plasma radius.

These profiles were chosen so as to best fit the results of the ORMAK temperature and density measurements relevant to this experiment. The piecewise linear temperature profile is consistent with the Langmuir probe and laser Thomson scattering measurements made at the 23.5-cm and 15.6-cm positions, respectively. The assumed density profiles are in agreement with the Langmuir probe data and satisfy the line average value ($\sim 1 \times 10^{13} \text{ cm}^{-3}$) obtained from microwave interferometer measurements. The three halves power law of the radial density dependence is typical of low current ORMAK discharges.¹ Calculations were also made with differently shaped, but consistent, profiles to test the sensitivity of the model to this parameter.

Finally, these profiles have been used to determine the instantaneous electron density and temperature along the injection path. Pellets were injected at 100 m/sec into the edge plasma along a path that makes an angle of 45° with respect to the plasma radius.

In Fig. 7 the results of calculations for different density profiles are compared. The plasma density profile between the liner and limiter edge for all these cases (0-0.3 msec) is held constant, but the plasma density within the main discharge varies according to the indicated power laws. The more steeply rising profiles give rise to more rapid evaporation and slightly shorter lifetimes, although the dependence is less than linear as indicated by the form of Eqs (1) and (2). All these profiles could be said to give good agreement with the data, but the preferred profile (three-halves power) best represents the overall observed results.

The comparison with experiment is shown by the solid line in Fig. 3. As concerns the pellet lifetime and general shape of the ablation curve, the agreement is good. The initial rapid rise in the ablation rate is a distinct feature of the experimental results which the theory does not reproduce. One possible explanation is that the temperature and/or density at the plasma edge is somewhat higher than the values used in the calculation. A factor of 2 increase in both temperature and density at the limiter edge would be sufficient to raise the initial part of the theoretical curve to the level of the experimental observations, and

Fig. 7. Ablation rates for 210- μ m-diameter pellets calculated for three different electron density profiles.

these new plasma conditions would still be within the range indicated by the Langmuir probe measurements. The assumed plasma profiles could also be somewhat erroneous because detailed information at the plasma edge is presently not available. A 1-cm uncertainty in plasma position with respect to the liner could also be a contributing factor.

The ablation cloud shields the pellet mainly from plasma electrons, and the amount of shielding depends on the plasma parameters as well as on the resulting density of the cloud. Calculations for the framing camera data of Figs 5 and 6 show that only about 8% of the incoming electron energy was shielded from reaching the pellet at the time of the first exposure at 140 μ sec. At the time of the largest cloud, 700 μ sec, 75% of the incoming electron energy was shielded by the ablation cloud.

The operating conditions under which the 70- μm pellet experiments were performed differed from the 210- μm series in that the density was about a factor of 2 larger and the temperature was perhaps 50 eV greater at the outermost laser diagnostic station. The results of the calculation performed with the appropriate plasma parameters are shown in Fig. 4 along with the data from four 70- μm pellet light bursts. The experimental record behaves in a fashion similar to the 210- μm series except that the background fluctuation level was larger in comparison to the lower signal level. The signal level was reduced because ablation rates were an order of magnitude smaller, as suggested by Eq. (2).

5. CONCLUSIONS

The injection of 70- μm and 210- μm pellets into tokamak plasmas has produced results which are consistent with a relatively simple theoretical model. This model explains both the lifetime of the pellets and their ablation time history, as observed by light signals emanating from excited hydrogen atoms in the gas cloud surrounding the pellets.

The pellets used in these experiments were only large enough to penetrate into the outer few centimeters of the ORMAK plasma. It is clear that larger pellets with higher velocities are needed to fuel even today's tokamaks. The theory discussed in Section 4 predicts that pellet lifetimes are proportional to the five-thirds power of the pellet radius. However, pellets cannot be made arbitrarily large; their size must be limited so as to contribute only a small fraction to the ions already present in the plasma. This limitation places a burden on increased pellet velocity. Table 2 gives predictions of the velocity to which pellets must be accelerated if they are to reach two thirds of the distance to the center of several tokamaks. Each pellet is assumed to contain 10% of the ion content of the tokamak, and injection is perpendicular. Central values for T_e and n_e are listed in Table 2, and the electron temperature profile is taken as $[1 - (r/a)^2]^2$ while the electron density radial profile is assumed to vary as $[1 - (r/a)^2]$. The extrapolations in Table 2 should be viewed with some caution, because the

simple physical picture assumed in Section 4 may be inadequate in the hotter, denser plasmas of larger tokamaks.

Table 2. Estimates of experimental pellet fueling requirements

Device	Device Characteristics			Pellet Radius (10^{-6}m)	Velocity (m/sec)
	a(m)	T_e (keV)	$n_e(\text{m}^{-3})$		
ORMAK	0.23	1.0	7×10^{19}	250	2500
ISX	0.25	1.0	7×10^{19}	285	2500
PDX	0.47/0.57	1.0	3×10^{19}	400	2000
PLT	0.45	1.7	5×10^{19}	410	4000

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