The Local Density Increment From an Ablated Deuterium Pellet in the TFTR Tokamak

D. K. Mansfield, A. Janos, D. K. Owens, G. L. Schmidt, M. G. Bell, A. Cavallo,
E. Fredrickson, A. T. Ramsey and G. Taylor

Princeton Plasma Physics Laboratory , Princeton University,
Princeton, New Jersey 08543

Details of the process by which ionized pellet ablatant increases the density in a tokamak have been observed for the first time. For mild ablation rates, this process is not simply diffusive. Instead, the ionized ablatant takes the form of a temporally symmetric pulse which propagates over large distances along magnetic field lines. This pulse has been observed both interferometrically and with an x-ray camera. These observations are not in qualitative agreement with models which predict a step-like densification of the plasma by the pellet.

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Measurements taken rapidly enough to resolve transient electron density phenomena due to ablated D_2 pellets have been made in the Tokamak Fusion Test Reactor (TFTR). The line-integrated measurements were made with a far-infrared laser interferometer sampling data at 100 kHz in ten vertical channels [1]. This rapid sampling and the close proximity (≈ 75 cm) of the pellet trajectory to the interferometer laser beams have facilitated the study of pellets and their remnants passing completely through the plasma column. Occasional pellet fragments which can pass completely through a thermally quenched ($T_e \approx 100$ eV) plasma column have also been studied. From this study has come the surprising observation that, for mild ablation, the density increment from ionized locally deposited ablatant (LDA) due to the pellet, its remnant or a fragment takes the form of a temporally symmetric pulse. It has further been observed that under some circumstances, this symmetric pulse appears to travel around the torus with little change in shape along magnetic field lines.

In this work, ablation of the pellet at the plasma edge or ablation of its remnant or of a fragment passing through quenched plasma are discussed. Thus, we are reporting on features due to mild ablation and deliberately avoiding a description of strong ablation phenomena. A mild ablation rate is here defined as $< 5 \times 10^{23}$ atoms/s which is $< 1\%$ of the maximum strong ablation rate achieved in these experiments.

In the experiments, frozen D_2 pellets were injected radially at 1.2 to 1.5 km/s into the midplane of D^+ ohmic plasmas. The cylindrical pellets (3.4 mm x 3.5 mm dia.) each contained $\approx 2 \times 10^{21}$ atoms. Typical target plasmas ($B_t = 3.0 - 3.5$ T, $I_p = 1.4$ MA, $R = 2.6$ m, $a = 0.96$ m, $q(a) = 4.5 - 5.2$) had central densities of $2.0 - 3.0 \times 10^{13} \text{ cm}^{-3}$ and central electron temperatures of 2.0 - 2.5 keV. In less than 2 ms after injection the central density increased to $2.0 - 2.5 \times 10^{14} \text{ cm}^{-3}$ while the electron temperature fell to 100 - 250 eV. Photographs indicate that the pellets did not curve toroidally during the 1.3-1.6 ms required to cross the plasma column.

Shown in Fig. 1 are the interferometer laser beams superimposed on a TFTR target plasma column. Mapped onto this is the temporal signal from a horizontally viewing D_α detector at the same toroidal location as the interferometer (18° toroidally from the pellet trajectory in the ion drift direction). The data shown are from a discharge in which a pellet crossed the plasma column and struck the limiter. The survival of the pellet remnant appears to be due to the extremely low temperature ($T_e \approx 100$ eV) in the inner half of the plasma column following deposition of pellet mass on its outer half. This low temperature dramatically reduces the ablation rate so that whatever fraction of the pellet remains when it reaches the core continues to travel toward the limiter while ablating only mildly and with dramatically reduced D_α emission.

Shown in Fig. 2 are density traces from the outer-most and inner-most interferometer channels (Chs. 10 and 1, respectively). On the time scale shown in the top half of this figure, the density appears to rise in a step-like manner. Because the rapid sampling rate used in these measurements allows for greater temporal resolution, a qualitatively different interpretation can be given to this rise. Upon expansion, the step-like rise of the density is seen to contain many features which have been found to be reproducible over many discharges. We begin a discussion of these features by pointing out that a narrow pulse (labeled LDA) appears sequentially in all channels starting with Ch. 10 and ending with Ch. 1. The leading edge of this pulse appears to "propagate" inward with a speed typically 5-8 % smaller than the initial pellet speed determined by its time-of-flight in the pellet gun [2]. The symmetric pulses connected by the straight line representing the pellet trajectory in Fig. 2 are thus interpreted as being ionized LDA propagating along field lines through the laser beams at the midplane after the pellet passes nearby. An interesting point is that the line-integrated density almost returns to its preexisting level after this pulse.

It is also seen in this figure that the density in Ch. 1 increases well before the arrival of the remnant and its associated LDA pulse. The leading edge of this increase is attributed to the arrival on the small major radius side of the torus of the ablatant originally deposited on the large major radius side. We refer to this increase as the remotely detected ablatant (RDA). The arrival sequence of the leading edges of the RDA on the inside interferometer channels (Chs. 1-5 , Fig. 1) is consistent with propagation of the ablatant along field lines. Further, the superposition of the LDA signature on the RDA is common to all the inside channels. This is taken to indicate that ablatant travels around the torus along field lines much faster than the pellet travels across the torus.

In Fig. 2, following the first LDA feature in Ch. 1, the pellet remnant strikes the limiter and sublimates causing a slow rise in the density (labeled puff). This puff is accompanied by a rise in the D_{α} radiation from the plasma edge (Fig. 1). After the remnant of the primary pellet has reached the limiter, a pellet fragment enters the quenched plasma column and generates its own set of LDA pulses (labeled fragment LDA) before striking the limiter causing a second gas puff. Also inserted in Fig. 2 are windows of data from Chs. 2 and 9. A second pulse is seen in Ch. 9 (and faintly in Ch. 10) and is believed to be RDA (labeled fragment RDA) originating from its point of creation as a fragment LDA pulse in the neighborhood of Ch. 2.

Attention should be given to the narrow pulse (labeled echo) in Ch. 10. This pulse is not due to a fragment because no fragment consistent with its timing was detected in the pellet gun, nor

does it appear sequentially in other channels. The presence or absence of this pulse is a *reproducible* feature that depends sensitively on the internal magnetic configuration of the discharge. Thus, it seems that this pulse is due to the ablatant propagating completely around the torus along field lines.

Shown in Fig. 3 are density traces for a case in which no echo or fragment was seen and in which the pellet did not reach the limiter. Seen on the leading edge of the RDA in Ch. 1 is a pulse superimposed on a gently rising background density. This should be compared to the RDA in Fig. 2 where no pulse is seen. For the discharge of Fig. 2, $q(a) = 4.5$ while $q(a) = 5.1$ for Fig. 3. Thus, the nominal difference between Figs. 2 and 3 is that the interferometer sampled the LDA and RDA in different magnetic configurations.

A symmetric pulse has also been seen at the plasma edge with a soft X-ray camera located 270° toroidally from the pellet injector [3]. Shown in Fig. 4 is the local emissivity measured along a horizontal chord passing about 5 cm inside the plasma edge at the top of the plasma. These data were taken during injection into a smaller discharge than those described above [4]. A field tracing code has shown that, for this discharge, the edge region sampled was connected over a distance of about 15 m along a field line to the region of ablation. A symmetric pulse is clearly seen superimposed on a rapid drop in the background emissivity. The initial drop is interpreted as due to a rapid fall in the electron temperature as the pellet enters and cools the discharge. The symmetric pulse is interpreted as the arrival at the camera of the ionized ablatant and corresponds to the density pulse seen by the interferometer.

Of available theories describing transport of ablatant, the most applicable to this work is that of Kaufmann *et al.* [5]. However, it should be noted that the predictions in Ref. 5 apply to a stationary H_2 pellet while our observations pertain to a moving D_2 pellet. In that regard, it is noteworthy that the time required for the pellet to cross each 4 cm wide laser beam was 30 μs while the resulting LDA pulse typically lasted 300-500 μs (see insert Fig. 3). Thus, the typical LDA pulse sampled by a laser beam reached a peak well after the pellet had passed beyond that particular laser beam and moved deeper into the plasma column. This slow rise is not consistent with the behavior predicted in Ref. 5 where it is shown that, for plasma conditions roughly similar to TFTR edge conditions, the density at ≈ 1 m from a stationary pellet should exhibit a rapid, step-like rise (rise time $< 10 \mu s$).

The data allows another aspect of the model in Ref. 5 to be tested. The lag time between the leading edge of the LDA in Ch. 10 and the leading edge of the RDA in Ch. 1 in both Figs. 2 and 3 is $\approx 200 \mu s$. For these discharges $q(a) > 4$ and the distance along a field line from the outside

(intersecting Ch. 1) to the inside (intersecting Ch. 10) is about 30 m (two toroidal transits). Thus, an average toroidal speed of 1.5×10^5 m/s can be estimated for the ablatant. This is twice the ion acoustic speed for 100 eV D_2 and is reasonably consistent with the speed predicted in Ref. 5 as well as with previous measurements of ablatant speed on TFTR [6].

Because of the proximity of the pellet and the interferometer, the electrons constituting a LDA pulse are assumed to be confined in a horizontal sheet of high density plasma that propagates along field lines which, in the geometry of Fig. 1, intersect the pellet orthogonal to its trajectory. At 1 m from the ablation event, the vertical thickness of this sheet should be ≈ 1 cm [5,7]. Assuming these sheet parameters, a typical peak line-average density in the LDA pulses would be 10^{15} - 10^{16} cm $^{-3}$ and each of these pulses would contain 10^{18} - 10^{19} electrons representing $<1\%$ of the D_2 in the pellet. These numbers are slightly higher than predictions of the Parks-Turnbull ablation model using TFTR pellet and edge parameters ($n_e \approx 7 \times 10^{12}$ cm $^{-3}$, $T_e \approx 150$ eV) [8].

Thus, even for mild ablation, at 1 m from the point of ablation the electron density increased by a factor of 10^2 - 10^3 . The resulting LDA pulses are reminiscent of the density-step excited ion acoustic soliton seen by Cohn and MacKenzie in a different plasma regime [9]. An intriguing feature of our data is shown in the Fig. 3 insert where the digital data points making up the LDA pulse are compared to the form to be expected if this pulse were a soliton [10,11]. Because of this reasonably good fit, one may speculate that this pulse is indeed a soliton. However, a difficulty with this hypothesis is apparent in Fig. 3 : the RDA pulse has started to rise in Ch. 1 before the trailing edge of the LDA pulse in Ch. 10 has returned to its baseline. If the LDA and the RDA features indeed represent the same pulse, we would conclude that its length is at least 30 m (two toroidal transits) which is much too long for an ion acoustic soliton. However, it is also possible that this RDA feature does not represent the propagation of a pulse but is, instead, an artifact of the line-integrated measurement. Field line modeling has shown that, for certain q-profiles, a pulse-like feature could be produced by the superposition of the leading edges of the RDA from the entire outer region of the plasma. Thus, any estimate of the length of the LDA based on its apparent overlap with the RDA must be considered speculative. It is hoped that future experiments will eliminate some of the uncertainties concerning the length and propagation properties of this pulse.

In summary, because the pellet does not increase the plasma density in a step-like manner, it appears that the densification process is not simply diffusive. Further, because the LDA pulse does not peak until well after the pellet has passed deeper into the plasma column, densification

from a mildly ablating pellet could be described as a two-step process involving rapid deposition of cold ablatant which is then heated by ambient plasma causing a pulse or perhaps counter-propagating pulses to form.

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FIGURE CAPTIONS

Fig. 1 A temporal D_α trace from the pellet is mapped onto the plasma column. A remnant struck the limiter as shown by the magnified D_α data. The interferometer laser beams and regions of strong and mild ablation are also shown. The average toroidal distance between the pellet trajectory and the laser beams is 75 cm.

Fig. 2 The density traces from Chs. 10 and 1 show the usual step-like increase due to the pellet but are full of details when expanded. Data from Chs. 9 and 2 (arbitrary units) are also inserted. The pellet/fragment trajectories are shown as straight lines. The pellet and fragment velocities are 1.26 and 0.92 km/s, respectively.

Fig. 3 The density traces for a case in which the pellet neither fragmented nor reached the limiter. The pellet trajectory is shown as a straight line. In the insert, normalized data points making up the LDA pulse are compared to $\text{sech}^2(t-t_0/\Delta)$ where $t_0 = 240 \mu\text{s}$, $\Delta = 74 \mu\text{s}$. The time needed for the pellet to cross the laser beam - the particle deposition time (τ_{PD}) - is also shown.

Fig. 4 The edge X-ray emissivity measured 15 m from the point of ablation. The data is magnified in the insert. The thickness of the vertical band is the uncertainty in the pellet entrance time.

Fig. 1

Fig. 2

Fig. 3

Fig. 4