PELLET ABLATION IN THE REVERSED FIELD PINCH AND TOKAMAK: A COMPARISON

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Introduction: While modelling of pellet ablation in plasmas using the neutral shielding cloud generated by the pellet gives general agreement with tokamak experiments,[1-3] many details are still not well understood. In particular, issues of ablation rate fluctuations, asymmetric cloud formation, pellet deflection, and self consistent effects of nonthermal energy and particle fluxes on the pellet (especially in auxiliary heated plasmas) require further consideration.

We compare the ablation of deuterium pellets with similar sizes and velocities in the ZT-40M reversed field pinch and ASDEX tokamak. While the two experiments have radically different plasmas, their effect on pellets is examined to illuminate similarities and differences in the pellet ablation physics. Photographs obtained both with still cameras and a fast gated-CCD video camera allow measurements of pellet cloud features, including intensity, curvature, velocity changes, cloud shape and striations. The shape of the pellet cloud and its light emission yield clues to processes in both the ablation layer and thermonuclear plasma.[4,5] Symmetry of the cloud is affected by the direction of the electron drift and magnetic field lines.[6] Gross track features, ranging from narrow, smooth and uniform, to broad and highly striated are noted, along with the corresponding plasma conditions that produce these features.

ZT-40M RFP: Injection of Deuterium pellets ($\sim 5\times10^{19} D^o$ atoms/pellet) at velocities of 400-600 m/sec into the ZT-40M reversed field pinch at Los Alamos[7] gives deep penetration and large $\Delta n/n$ refuelling. Typical pre-pellet plasma parameters are $I_\phi \sim$ 120-250 kA, $\bar{n}_e \sim$ 1.5-3$\times10^{13}$cm^{-3}, $T_e(0) \sim$ 150-300 eV, and global $\tau_E \sim$ 150-400 μsec. However, enhanced ablation in the outer plasma regions, stronger from the electron drift side than the ion side, results in extreme trajectory curvature.[8] A small population of energetic electrons ($\sim$ 1-10 keV) directed along magnetic field lines from the electron drift direction, would be sufficient to account for the obsverved motions assuming that asymmetric ablation rates (of order 30-100%) cause rocket-like acceleration of the pellet.

Images of the pellet taken every 100 μsec, with 5 μsec exposures, show the pellet cloud is brightest in the plasma edge region, with intensity decreasing through the plasma core.[9] Lineouts of these images show bright centrally peaked emission clouds with typical FWHM dimensions of $\sim$ 1.5 cm. A weak comet-like tail is often visible. The track gets narrower over the course of the pellet lifetime ($\sim$600-800 μsec). The pellet trajectory curvature is generally reproducible, although succesive pellets may be shielded by the first, and have less deflection.[8] Highly deflected pellets undergo significant velocity changes. Depending on the relative direction of the pellet velocity and electron drift (magnetic field direction), the pellets are observed to speed up, or slow down in the plasma. In extreme cases the pellet may be stopped, or even have its trajectory turned around in the plasma! In the plasma edge region, where the magnetic field is nearly poloidal, the deflection is poloidal, whereas in the plasma core region (with a principally toroidal field), the deflections are more toroidal.

ASDEX Tokamak: A variety of pellet sizes are possible in ASDEX,[10] typically $4x10^{19}$ ("small") but ranging to $1.4x10^{20} D^o$ atoms/pellet ("large"), with a typical pellet velocity (for the centrifuge injector) of 570 m/sec. The plasma volume of 5.2 m^3 is about 5× larger than ZT-40M, and for ohmic conditions, a typical plasma is $I_\phi \sim$ 320-450 kA, $\bar{n}_e \simeq 1.5\text{-}4\times10^{13}\text{cm}^{-3}$, $T_e(0) \simeq 1.0\text{-}1.5$ keV, and global $\tau_E \sim 60\text{-}80$ msec.

We have recently installed the gated-CCD camera on ASDEX, and used it to obtain time resolved images of the pellet clouds. In situ pellet velocity remains close to that from the gun, although significant toroidal velocities can occur in the later part of the pellet lifetime. Velocity measurements are complicated by uncertainties in the pellet location within the dynamically evolving pellet cloud. Figure 1 shows a CCD photo (a), looking down on the pellet track from an angle of 75-45 degrees to the vertical, and corresponding densitometer lineouts, as well as the wide-angle spatially integrated $D_\alpha$time history (b), of the pellet ablation. The darker central region in each bright cloud, with dimensions of 2 cm diameter, seen in the lineouts of Figure 1(b), is difficult to explain based on self absorption alone. Also, bumps or protrusions of the cloud, in the direction of pellet motion, suggest that the light emission is dynamically evolving, and is "left behind" as the pellet moves on. Precise location of the pellet is made difficult by the changing shapes of the light emitting region. Cross field dimensions of the cloud are ~ 1 cm radius, while along the toroidal field dimension, the elongated FWHM diameter is 5-7 cm, as seen in these 2μsec exposures. Collapse of the old emission region surrounding the pellet is strongly suggested by time resolved photos on ASDEX, and has also been reported in TEXT.[11] This darker central region near the pellet is not seen in experiments where the luminous region remains "spherical", as was always the case in ZT-40M, where the pellet tracks were uniformly smooth, and striations were the rare exception rather than the rule. This may have also been the case in ORMAK.[6]

An assortment of time-integrated ASDEX pellet photos are shown in Figure 2. The plasma separatrix is at r$\simeq$ 40 cm, although the pellet light emission first begins at r= 42-41 cm, near the bottom of each picture. The field of view extends radially from r= 44 cm to r=0 cm, and a reference picture with ruled 10 cm marks is shown for calibration. Two pellets from a multi-pellet sequence in the same ohmic discharge (#21143) are shown Fig. 2(a) and (b). The first is at 1.0 seconds and the fourth at 1.3 sec with a higher density of $\bar{n}_e = 4.6\times10^{13}\text{cm}^{-3}$. For lower electron densities, and/or higher T_e, the toroidal extent of the cloud is larger. Pellet trajectories are straighter, or curve in the ion drift direction with the application of significant Neutral Injection, as shown in Fig.2(c), shot #23216 with a "large" pellet, I_ϕ=385 kA, B_ϕ=2.21 T and 2.6 MW of co-beams. One of the largest toroidal deflections seen for pellets in ASDEX is shown in Fig. 2(d), where the 7^{th} and 8^{th} pellet (30 msec apart) in a 380 kA weak NI shot #21559 (0.35 MW co-beams) can be seen turning nearly 90^o.

A transition between a relatively smooth ablation track, and an oscillating, or striated track, is commonly observed in the edge region, and can be seen in Fig. 2(a) (if the reproduction is good enough!). Durst[11] has associated this transition from smooth to non-symmetric (and oscillating) light emission with the q=2 layer in the TEXT tokamak. We see no correlation with the smooth/oscillating track boundary to the q value. In particular, beams force the oscillations to begin even closer to the plasma boundary than the usual 5-6 cm depth in ohmic discharges, for the same q at the edge. Also, ohmic discharges with q=1.95 at the plasma edge, still have a well defined smooth track zone, before the striations begin.

Discussion: The time development of the pellet ablation rate is dependent on the type of plasma conditions that are encountered. It is striking to compare the typical ohmic tokamak pellet ablation time history, with that of a pellet ablating in the ohmic reversed field pinch. Usually in the tokamak discharge, the pellet ablates at first slowly, then ever more rapidly, with a sharp falloff in time as the pellet is consumed. In contrast, the RFP pellet time history is nearly the opposite....that is, the pellet light emission is strongest near the edge of the plasma, and then decreases as it nears the center. Tokamak discharges with large runaway content, or even neutral beam heating, also show enhanced edge ablation.[1,12] Unlike runaways in tokamaks, the energetic electrons in the RFP are evidently not of high enough energy to cause bulk heating of the pellet (and hence its explosive demise), and instead the pellet remains intact.

Striations are a common feature in the tokamak, and even stellarator discharges.[6,1,13] However, uniform, smooth bending tracks can also occur in tokamaks when pellets are fired early during the current rise phase.[5] A model of a neutral cloud being alternately formed, and then left behind as the pellet edges out of the dense cloud shielding influence, lends itself naturally to an oscillatory explanation of the pellet ablation rate. An instability in the neutral shielding cloud can evidently be triggered by as yet unspecified plasma conditions. The association of a dip in the light intensity in the ablatant cloud, with the presence of the instability, remains to be tested. Plasmas/pellets without striations may hold the key to the instability trigger conditions. We note, that for sufficiently short energy confinement time (ie, the tokamak edge, or todays RFP plasmas) compared to the time the pellet spends in these regions, smooth ablation of the pellet should be expected, since the energy will "fill in" locally faster than being depleted by the pellet. This may explain why in ZT-40M, striations were almost never visible, since the pellet cloud basically sampled the entire plasma energy flux during its lifetime, due to the short global energy confinement time of the pinch. Also, conditions which bypass the neutral shielding cloud (ie, energetic fluxes of particles), should also have smoother pellet ablatant tracks.

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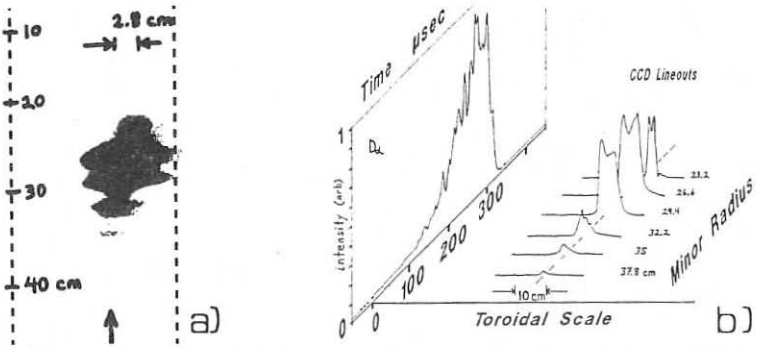
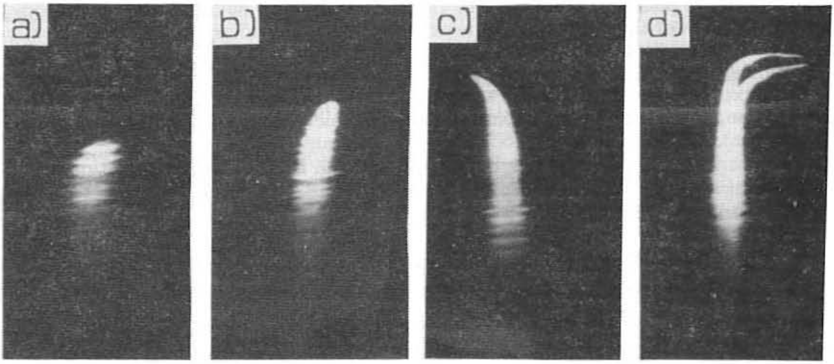


Figure 1: Deuterium pellet ($4x10^{19}$ D^o atoms) at 570 m/sec, ablating in an I_ϕ = 380 kA diverted ASDEX ohmic shot #26082. (a) Multiply-gated CCD picture (2μsec exposure every 50μsec). (b) Lineouts of the elongated (along field lines) cigar-shaped emission clouds show diminished emission in the central region of the brightest clouds, and $D_\alpha$emission on the dual time/penetration depth axis.



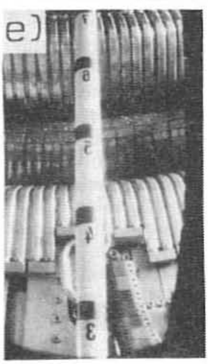


Figure 2: Top-view, time integrated ASDEX pellet photos. (a) Ohmic I_ϕ=350 kA, B_ϕ=2.49 T, $\bar{n}_e$=$3.4x10^{13}cm^{-3}$, "small" pellets, (a) first pellet and (b) fourth pellet. The striation (oscillation) frequency is about 75 kHz. (c) 2.6 MW Neutral injection, curvature in ion drift direction. (d) Strongest pellet curvature seen in ASDEX. (e) Reference photo, with radial calibration rod, marks every 10 cm. The diameter of the rod is 28.5 mm. The r=40 cm position is at the inner edge of the black mark, just above the inverted "3" on the rod. Due to lenses, the photos are inverted left-right, so the plasma current and toroidal field directions appear as if oriented from right to left, and drifting electrons impact the pellet cloud preferentially from the left side. The horizontal curved arc is light from the lower divertor throat.