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Pellet Imaging Techniques on ASDEX

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As part of a USDOE/ASDEX collaboration, a detailed examination of pellet ablation in ASDEX with a variety of diagnostics has allowed a better understanding of a number of features of hydrogen ice pellet ablation in a plasma. In particular, fast gated photos with an intensified Xybion CCD video camera allow in-situ velocity measurements of the pellet as it penetrates the plasma. With time resolution of typically 100 nanoseconds and exposures every 50 microseconds, the evolution of each pellet in a multi-pellet ASDEX tokamak plasma discharge can be followed. When the pellet cloud track has striations, the light intensity profile through the cloud is hollow (dark near the pellet), whereas at the beginning or near the end of the pellet trajectory the track is typically smooth (without striations) and has a gaussian-peaked light emission profile. New, single pellet Stark broadened D_α, D_β, and D_γ spectra, obtained with a tangentially viewing scanning mirror/spectrometer with Reticon array readout, are consistent with cloud densities of $2\times10^{17}cm^{-3}$ or higher in the regions of strongest light emission. A spatially resolved array of D_α detectors shows that the light variations during the pellet ablation are not caused solely by a modulation of the incoming energy flux as the pellet crosses rational q surfaces, but instead are a result of a dynamic, non-stationary, ablation process.

I. 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.

The shape of the pellet cloud and its light emission yield clues to processes in both the ablation layer and fusion plasma.[4,5] Symmetry of the cloud is affected by the direction of the electron drift and magnetic field lines.[6,7] Striations are a common feature in the tokamak, and even stellarator discharges.[6,1,8] However, uniform, smooth bending tracks can also occur in tokamaks when pellets are fired early during the current rise phase.[5] Measurements of striation angles have been utilized to infer plasma q-profiles.[5,9] Consequently it is useful to understand the mechanisms leading to striation formation.

As part of a USDOE/ASDEX collaboration,[10] a detailed examination of pellet ablation in ASDEX with a variety of diagnostics has allowed a better understanding of a number of features of hydrogen ice pellet ablation in a plasma. We describe here the complement of pellet diagnostics in use on the ASDEX tokamak, along with typical results and some insights from these measurements. Because of the availability of a rather complete plasma diagnostic set on ASDEX, as well as both a centifuge multi-shot and gas-gun single shot pellet injector, ASDEX is a well-suited device for such studies.

II. GENERAL

The ASDEX pellet diagnostic set includes the usual pellet gun diagnostics of light gates and microwave cavities for initial pellet timing, velocity, and mass measurements respectively. Then, as the pellet enters the plasma it becomes visible to several wide angle, white light photodiodes, viewing from behind the pellet as well as tangentially. A seven channel filtered and tightly collimated photomultiplier array views the pellet track in a poloidal fan, also from behind the pellet in the toroidal midplane. Single shot spectral broadening measurements of the Balmer series emission from the pellet are obtained with a Reticon array coupled to a 1 meter visible spectrometer, able to view the pellet track tangentially via a remote manipulator mirror system. Still images of the pellet are obtained tangentially, and from a position above the pellet track. The so called "top view" camera was then replaced with a fast gated CCD video camera to obtain time resolved images, in a manner first employed on the ZT-40M reversed field pinch at Los Alamos.[11] These allow measurements of pellet cloud features, including intensity, curvature, velocity changes, cloud shape and striations.

The geometry for these pictures relative to ASDEX is shown in Figure 1. The nominal plasma separatrix is at r = 40 cm, although significant ablation of pellets usually first begins near r=41.5 cm. A calibration photo, with a measuring staff (diameter 2.85 cm, with 1.9 cm thick black bands every 10 cm), extending from the plasma edge to just beyond the plasma axis at the top of the picture is shown in Fig. 1(a). The equivalent side view is seen schematically in Fig. 1(b).

A variety of injected pellet sizes are possible in ASDEX,[12] from 4x10^{19} ("small") to 1.4x10^{20} D^o atoms/pellet ("large"), with a typical pellet velocity (for the centrifuge injector) of 570 m/sec, and up to 50-60 pellets per discharge if desired. A single-shot gas gun, now in use on Wendelstein WVII-AS, capable of a range of pellet velocities from 300-900 m/s at the end of a 3-meter weakly curved guide tube, was also employed to inject neon and argon impurity-doped deuterium pellets, as a second round of such work on ASDEX.[13] The ASDEX plasma volume is 5.2 m^3, and for ohmic conditions, a typical plasma has $I_\phi \sim$ 320-450 kA, $\bar{n}_e \simeq$ 1.5-4$\times 10^{13}$cm^{-3}, $T_e(0) \simeq$ 1.0-1.5 keV, and global $\tau_E \sim$ 60-80 msec. Additionally, target plasmas with up to 2MW of Neutral Beam Injection, or 2MW of Lower Hybrid Wave power, or 4MW of ICRF power were available for comparisons.

III. GATED VIDEO CAMERA

A recently installed Xybion ISG-02 gated-intensified CCD video camera was used to obtain time resolved images of the pellet clouds. With a 600 mm camera lens, images of a small reentrant objective/relay lens could be obtained with good depth of focus, and a wide field of view across the outer minor radius of the plasma, including the separatrix and scrapeoff region. Typical exposures for the 256 gray-scale digitized grey-scale video images ranged from 0.1-2 μsec, at an aperature of f/64 with an ND 1.0 neutral density filter, depending somewhat on the pellet size and presence of auxillary heating (which results in brighter pellets). Real time video capture is achieved for thirteen 320x240 pixel fields with a frame-grabber equiped PC-AT. The entire shot is simultaneously stored to videotape for off-line replay and capture. Repetitive images of the same pellet are obtained on one video field by sending a gating pulse over a 50-meter control cable from the ASDEX control room, usually every 50 μsec.

The Xybion camera was located in magnetic fields of a few hundred Gauss, at a distance of 2 meters from the toroidal field coils, without electronics problems. We have also identified a commercial color Panasonic WV-CD1 minature CCD camera that functions in fields of excess of 1.5 T. On ASDEX-U a modified Sony B&W 570x485 pixel CCD camera, model XC-77, which has been tested to function in fields of 1 T or greater, will be employed with a gated multichannel plate for time resolution. Both of these cameras have separate head and electronics sections.

A typical 600 m/sec pellet abiating over a period of 300 μsec gives 5-6 images on the video field. The motion of the pellet provides separation of the images. Not surprisingly, slow pellets, at 210 m/sec, required settings of 100 μsec between exposures for reasonable separation, but rather unexpectedly still provided 7-9 images on the field (they last longer than a faster pellet)! Due to a persistance problem on the intensifier phosphors and/or incomplete readout of the CCD charge buckets, it was necessary to wait 70 msec between pellets to avoid an afterimage problem when imaging multiple pellets. In situ pellet velocity, determined from measurements of the positions of subsequent exposures and knowing the time between exposures, remains close to that from the gun in most cases, although significant toroidal velocities can occur in the later part of the pellet lifetime. The most highly deflected pellets in ASDEX show a large boost in toroidal velocity, and slowing of the radial component, most likely due to differential ablation and "the rocket effect".

Figure 2 shows time resolved CCD photos of a number of pellets, looking down on the pellet track from an angle of 75-45 degrees to the vertical, with a nearly identical view as shown in the previous Figure. This angle complicates the cross-field analysis by combining the relatively wider poloidal extent of the clouds with the narrower radial dimensions. The actual cloud shape tends to be an elongated (along toroidal field lines), flattened (in the poloidal sense) cigar. Comparable time-integrated photos are published elsewhere.[11]

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, as has also been observed by Durst.[15] The precise location of the pellet is made difficult by the changing shapes of the light emitting region. Radial dimensions of the clouds range from 1 cm to 3 cm diameter in Figure 2, and the elongated FWHM diameter varies from 3 cm to more than 10 cm in these photos. Higher density target plasmas generally yield smaller pellet clouds. In the opposite extreme, cases of pellets injected directly into Lower Hybrid heated plasmas result in cloud sizes larger than the camera field of view (toroidally), with extremely poor pellet penetration (only a few cm), similar to that reported in ECRH discharges on TFR.[16]

With time-integrated images, a transition between a relatively smooth ablation track, and an oscillating, or striated track, is commonly observed in the edge region of the tokamak. Densitometer scans across the smooth zone, show peaked light emission, while scans in the toroidal direction after the onset of oscillation show a hollow light emission profile.[11] 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.[9] The 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,[14] 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]

On TEXT, the transition from smooth to non-symmetric (and oscillating) light emission has been associated with the q=2 layer.[15] 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. We think the answer to the transition is clearly demonstrated with the following diagnostic, and is the result of the onset of a periodic ablation instability.

IV. POLOIDAL FAN ARRAY

By coincidence, an eight-channel array of photomultipliers designed to image the outer midplane separatrix edge plasma for fluctuation studies,[17] was at the same toroidal location as the newly installed single-shot gas gun pellet injector. A high pass red filter (Kodak 91, T=0.4% at 620 nm, 51% at 640 nm and 86% at 680 nm) was employed. The array consists of separate optical fibers, placed 12 mm apart vertically at the image of the plasma edge as projected by a 10 cm diameter, 64 cm focal length lens, which is positioned 128 cm from the plasma edge. The result is that at R=195 cm in the plasma, the effective poloidal (vertical) spacing of the chords is 1.3 cm, and the footprint of each chord is 0.9 cm diameter This is useful when estimating the poloidal expansion velocity of the light emitting part of the pellet cloud.

We were able to sample the pellet cloud light emission at digitization rates of up to 10 MHz, and found the cloud fluctuations (striations) to be in the range of 35 140 kHz. The higher end of this frequency range is generally found as a pellet penetrates further into the plasma. We found extremely regular oscillations were produced with moderate neutral beam injection, compared to ohmic heating alone, and that the frequency is higher in the former case. Under these circumstances, images show the pellet cloud to be smaller, and therefore consistent with the $r_o f = v_p$ model (where r_o is the cross field filament radius, v_p is pellet velocity, and f is the fluctuation frequency) employed by several authors.[15,16] Phase shifts across the array are substantial, indicating a poloidal expansion of the region of maximum light emission perpendicular to the toroidal magnetic field at velocities of 4 6×10^5 cm/s, consistent with an ion sound speed of less than 1 eV. This smearing contributes to a masking of the true level of the fluctuations if only observed by the usual wide angle photodiode. A signal from a wide angle diode, and from the central chord of the tightly collimated array are shown in Figure 3, for the same pellet. The spectacular modulation depth of the tightly collimated chord compared to the usual wide angle view is evident. It was this type of data which suggested that the oscillations are not a second-order effect, but actually dominate the ablation process, leading to a new analytic and computer model of the shielding cloud formation and dynamics.[18]

V. STARK BROADENED PROFILES

As a new computer-controlled stepping-motor driven manipulator-mirror system came on-line in 1989 in ASDEX,[10] it was aligned to allow tangential views towards the pellet injection ports. A beamsplitter permitted simultaneous standard video camera views, while the bulk of the light was directed into a 1-meter B&M Spectronix visible light spectrometer coupled to a 1024 element Reticon array (of which 800 pixels are usable due to a smaller sized intensifier), with 120 or 250 Å spectral coverage. The field of view was a vertical slice, approximately 2 cm wide, by 8 cm tall, across the pellet flight path. Resulting single-pellet, time integrated (readout $\Delta t = 17$ ms is much larger than the pellet lifetime) line profiles of D_α, D_β, or D_γ emission from the pellet cloud were obtained. Spectral data from a shot with multiple pellets is shown in Figure 4. In this instance, large deuterium pellets were injected every 50 msec into an I_ϕ=380 kA plasma heated with 1.6 MW of ICRH power at frequency $2\Omega_H$. The observed FWHM of 70-75 Å of the D_β spectral line is consistent with average densities of order $2\text{x}10^{17}\text{cm}^{-3}$, assuming an LTE model.[20] Based on the relative brightness of the background plasma line, we know that this for this particular case, the field of view was not centered on the brightest part of the pellet cloud. The decrease at line center is expected, but unfortunately a laser burnspot on the array is also contributing slightly in this instance! Successive pellets are seen to have similar broadening. These results are in general agreement with similar measurements on PLT, TFTR, TEXT and TFR.

VI. DISCUSSION

We have shown new measurements of pellets in the ASDEX plasma, with a variety of time, space, and wavelength resolving diagnostics. When combined with a different target plasmas and even pellet injectors, we have been able to see the pellet ablation process from a better viewpoint, resulting in a new model for the dynamics of the non-stationary pellet cloud shielding. 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. This was first suggested by Büchl[8] and has been qualitatively described by Durst.[15]

The association of a dip in the light intensity in the ablatant cloud with the presence of the instability,[14] has now been modelled, and a hollow ablatant profile is a key requirement for the ablation instability in the theory, and highly suggestive of the hollow light profiles seen in the experiment. This is described by Neuhauser and Wunderlich,[18] with the key finding being that both a critical ablation rate threshhold and a hollow cloud profile are required to obtain an oscillating ablation rate. The net result of the pellet ablation oscillations, is a reduction in the pellet penetration depth relative to a hypothetical case without oscillations. An interesting prediction of this model, is that the spatial scale length of the instability varies from one to two times the cloud ionization radius, for different cloud profiles, depending on the degree of instability. Experimental tests with widely differing pellet velocities, indicate that the ablation instability frequency is not a simple linear function of the pellet velocity, but complicated by background plasma conditions. However, the idea of resonant q-surfaces being solely responsible for the fluctuations, is eliminated by slow pellet experiments, where many more periods of oscillation are seen as the pellet travels through the same plasma region, compared to a faster pellet.

Details of striation frequency, dependence on pellet velocity, size, and conditions for the onset (and demise) of the instability are under investigation, with the intent to provide sufficient input for comparisons to code modelling, and coupling of this new physics into predictive codes for future devices.

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Figure 1: (a) White light reference photo with radial calibration staff along flight path of pellets from the centrifuge injector. The r=40 cm position is at the inner edge of the black mark, just above the left-right inverted "3" on the rod. (b) Schematic cross section of ASDEX, depicting the field of view for the "top-view" camera, as seen from side on.

Figure 2: Time-resolved, multiply-gated CCD pictures (0.3 μsec exposure every 47 μsec), for a variety of plasma conditions. The toroidal electron drift direction is from left to right in the photos, and the pellets enter the plasma radially with a velocity of 570 m/s, from the bottom of each photo. In each case, I_ϕ=320 kA, B_t=2.17 T, and density before the beginning of the pellet sequence was $\bar{n}_e$=1.4x10^{13}cm^{-3}. (a)Shot 26454, 4^{th} pellet, 200 msec after Lower Hybrid shutoff. (b) Shot 26459, no LH, 4^{th} pellet. (c) Shot 26458, no LH, first pellet. (d) Shot 26461, second pellet, 140 ms after shutoff of 0.5 MW LH power. Note the enlarged toroidal extent of clouds.

Figure 3: The ablation instability as seen by (a) wide angle and (b) narrow field of view light emission detectors. Shot 27516, a 4% neon-doped deuterium pellet with v_p=523 m/s initial velocity, I_ϕ=320 kA, B_t=2.18 T, with 1.1 MW neutral beam injection power.

Figure 4: Stark broadening of D_β light from the pellet cloud, for multiple pellets, during ASDEX shot 28531, obtained with a free-running Reticon array. Note the lower level, and narrower emission from the background plasma line prior to the pellet sequence.

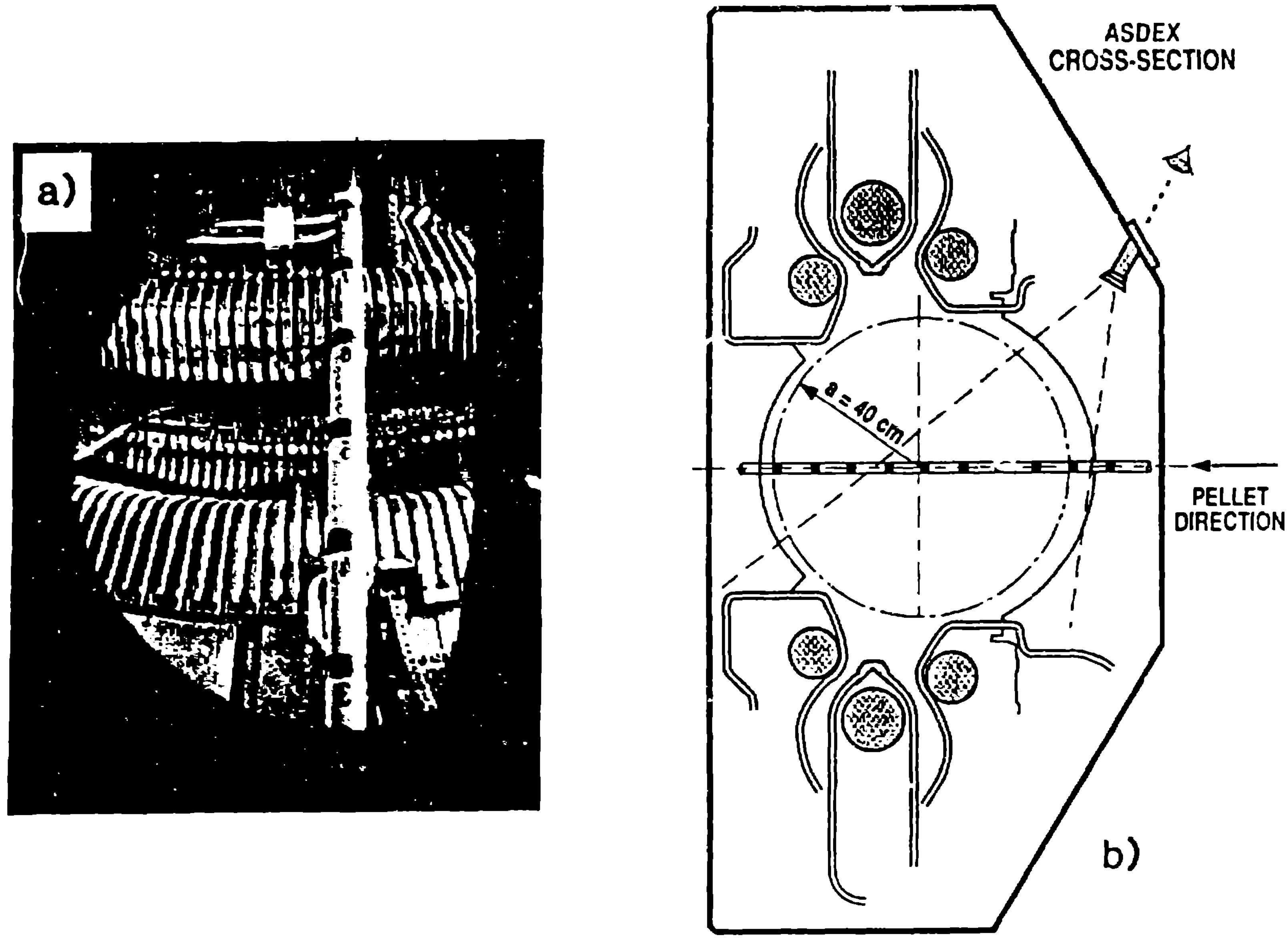


Fig 1

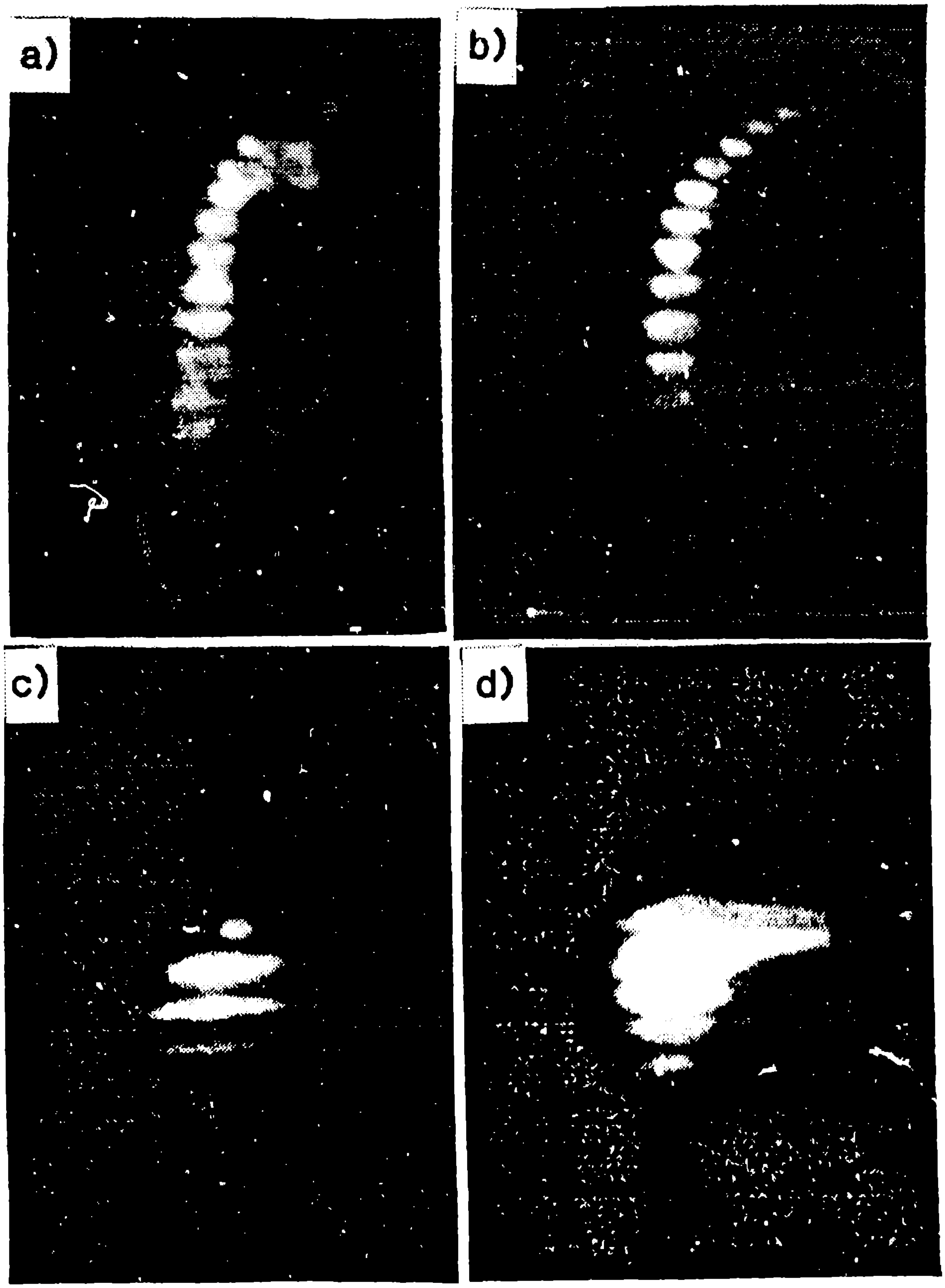
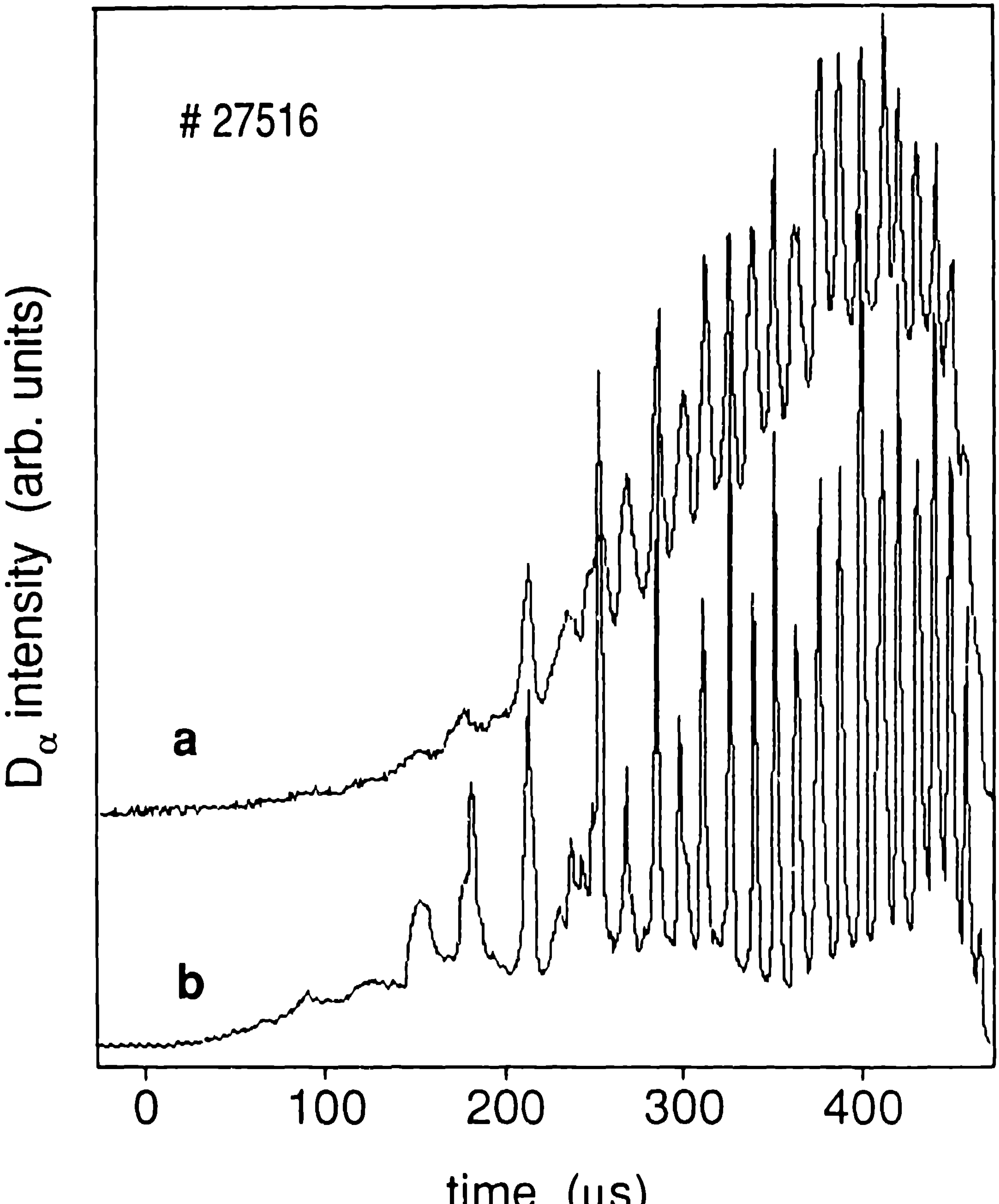


Fig. 2

Fig 3



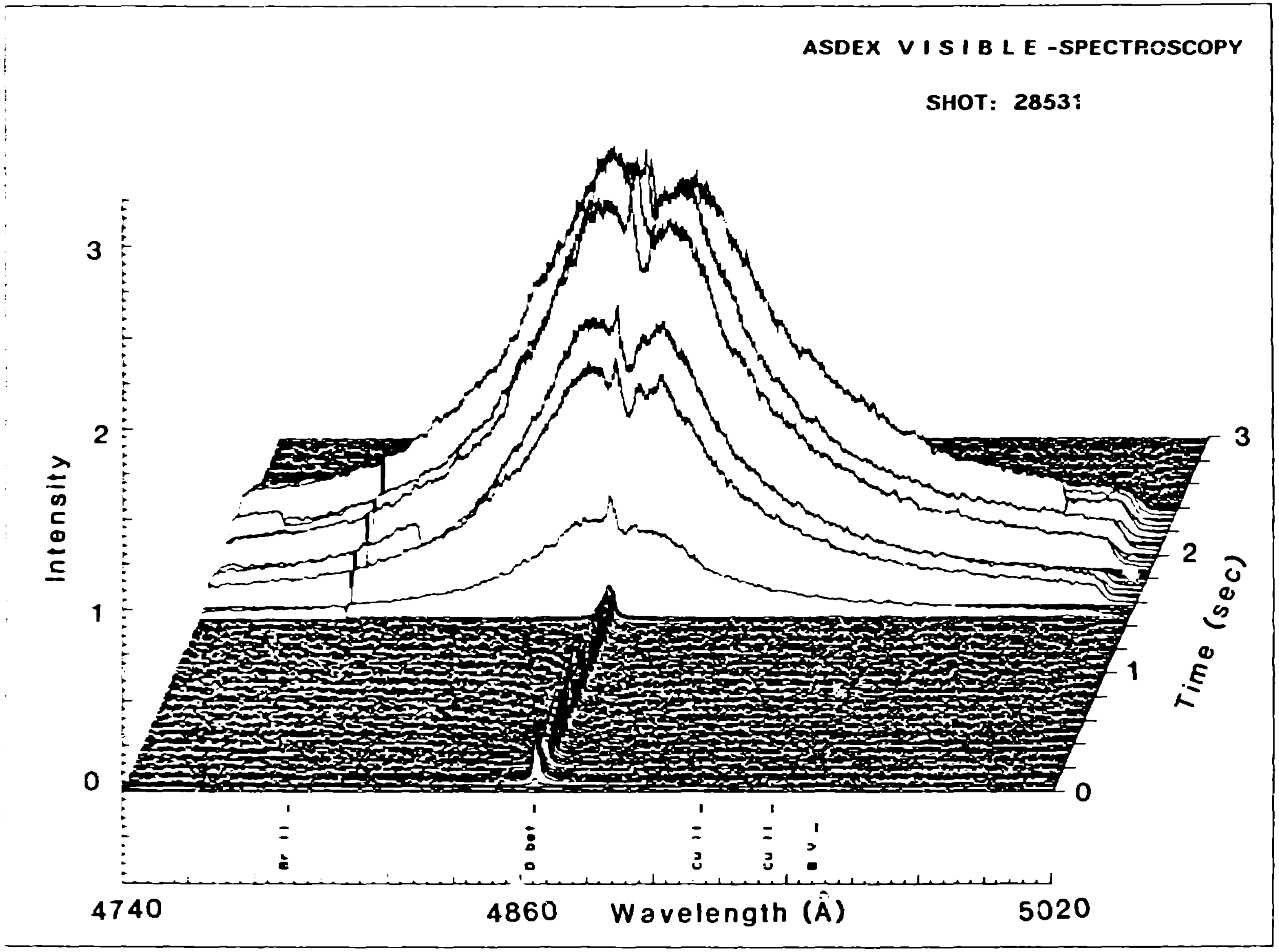

ASDEX VISIBLE-SPECTROSCOPY
SHOT: 28531
Intensity
3
2
1
0
Time (sec)
3
2
1
0
4740
4860
Wavelength (Å)
5020

Fig 4