Studies of C-pellet ablation cloud structure on Wendelstein7-AS stellarator

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Introduction. Predictions of the particle deposition profiles produced by ablating pellets in tokamaks and stellarators are fundamentally interesting for such applications of pellet injection as fuelling, diagnostics and burn control [1], [2]. Studies of the pellet ablation cloud structure using photographic technique could clarify the mechanisms of the basic physical processes of the pellet-plasma interaction. In this paper, we present results of the ablation cloud structure observations in carbon pellet experiments at W7-AS and compare them with those obtained elsewhere.

Experimental set-up. Carbon pellets of 0.35-0.45 mm in size and with 150-400 m/sec velocities were injected in the plasma core direction at ~15^o below the equatorial plane. Cloud intensities passing through an interference filter with $\lambda = 723$ nm and $\Delta\lambda_{FWHM} = 9.3$ nm (724 nm CII line) were observed using three different schemes: (1) one CCD camera image with a 10 ms exposure time that is much longer than the pellet ablation time ~ 0.5-1 ms; (2) a sequence of snapshots from a fast CCD camera (exposure time 2 µs, repetition time 20-30 µs); (3) two instant snapshots, one by each of two synchronized fast CCD cameras (exposure time 5 µs). Viewing directions of measurements were as follows: from the bottom, in direction almost transverse to a pellet flight path for schemes (1-3), and, in addition from the rear side of a pellet track for scheme (3). Scheme (3) allowed us to obtain instant pictures of the cloud radiation intensity distribution from two directions simultaneously. The pellet trajectory has been fitted to the magnetic flux map with fairly good accuracy (~ 1 cm). Details of the experimental set-up are described in Ref. [3].

Radial cloud asymmetry. The typical example of the ablation CII cloud photos is shown in Figs. 1c-e for the W7-AS #49965 shot ($R_0 = 2.05$ m, $a = 0.17$ m, $B = 2.55$ T, $\iota = 0.35$, $T_e(0) = 1.6$ keV, $n_e(0) = 5.2\cdot10^{19}$ m^{-3}, $P_{ECRH} = 900$ kW, $d_p = 0.395$ mm, $v_p = 250$ m/s. In Fig. 1e, an ‘integrated’ photo, obtained using scheme (1), is shown. The magnetic field line direction on the image plane is roughly vertical, and the direction of pellet velocity is shown

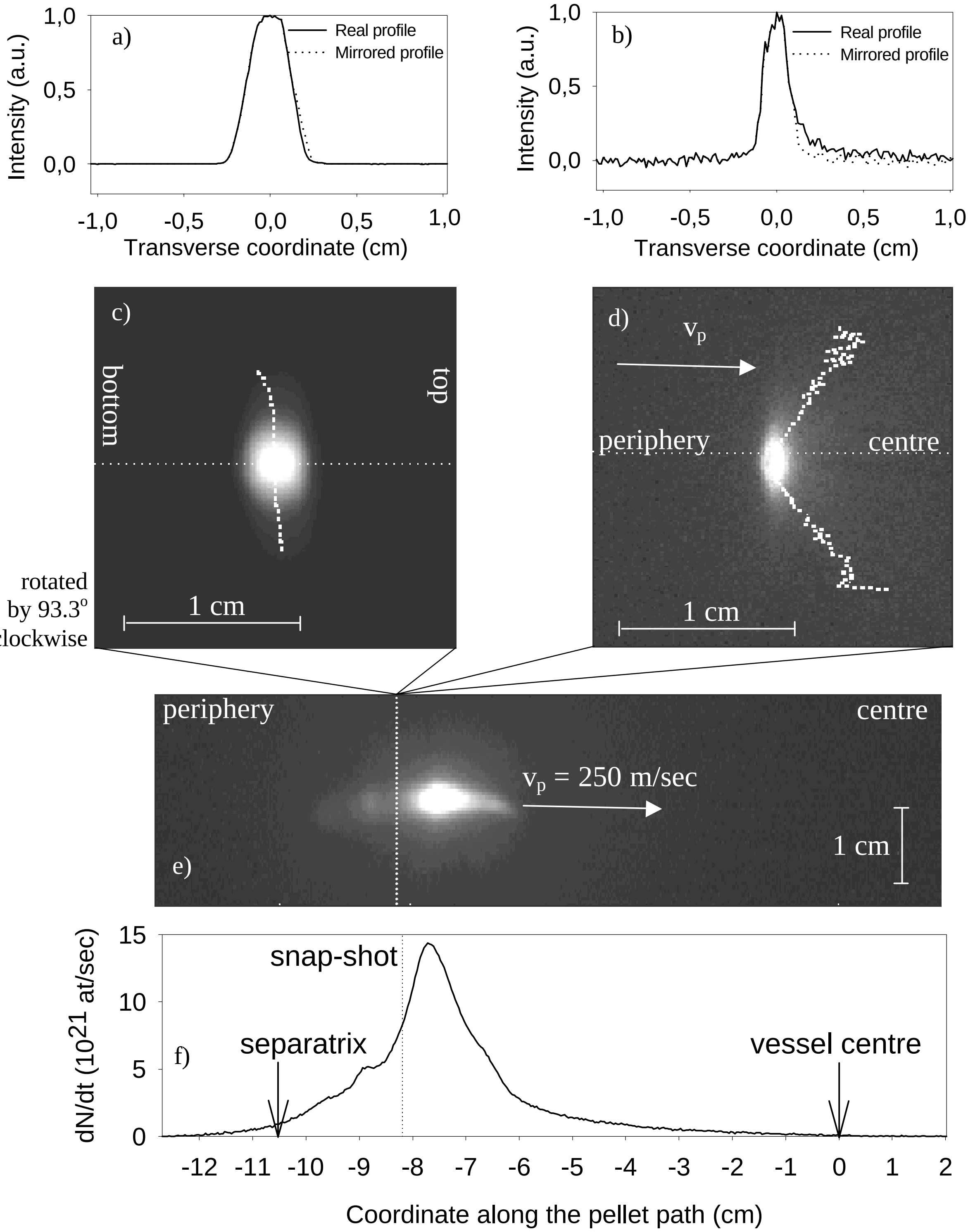

Fig. 1. Images of the pellet ablation cloud #49965 and intensity profiles: (a) and (b) – intensity profiles in transverse direction, (c) and (d)–snapshots from behind and from below, (e) – integrated photo from below, (f) – pellet ablation rate profile deduced from photo (e).

by the arrow. At each moment, the cloud is assumed to be elongated in the magnetic field direction and the pellet is being situated in the centre of such cloud [3]. The ablated material spreads along the local magnetic surface, and the instant total cloud light emission is supposed to be proportional to the pellet ablation rate [3] that allowed us to evaluate the ablation rate profile shown in Fig. 1f. The moment of the two snap-shot photos made using scheme (3) is denoted by the vertical dotted line in Figs. 1f and 1e. The instant photo shown in Fig. 1d was made from the same direction as the integrated photo. The instant photo in Fig. 1c was made almost from the rear side of the pellet path. The magnetic field line direction in Figs. 1c, 1d is vertical. The thin dotted lines in Figs. 1c,d denote the direction perpendicular to the magnetic field direction. Solid lines in Figs. 1a and 1b show cloud radiation intensity profiles along these lines correspondingly.

The cloud in Fig. 1c seems symmetric, while in Fig. 1d a cloud asymmetry is visible. Dots define positions where the integrals of the cloud intensities along a horizontal line are equal on the left and right side. They form an “averaged line” which is almost straight in Fig. 1c and trends to the plasma center in Fig. 1d. Furthermore, one can see that the profile in Fig. 1a is symmetric in the transverse direction, while the profile in Fig. 1b is asymmetric – its right wing decays slower than the left wing. To make this difference more evident, a part of the left wing was mirrored and plotted by dotted line in Fig. 1a,b. The cloud symmetry in the vertical direction and asymmetry in the radial direction are typical and well reproduced in a number of shots.

The asymmetry of the snap-shot clouds in the radial direction discussed above may be explained by the radial drift of the cloud plasma towards the plasma centre. The direction of this drift differs from results of similar experiments on tokamaks, where the hydrogen cloud plasma drifts in the opposite direction (i.e. outwards the plasma core) have been observed [4], [5]. The tilt angle of the ‘average line’ and the assumption of sonic speed of the cloud plasma with temperature $T_{cl} \approx 1$ eV allows us to estimate a drift velocity of ~1 km/sec which is one order of magnitude less than those evaluated in [4], [5].

Cloud toroidal decay length. The cloud decay length λ in the magnetic field direction has been evaluated using photos obtained in CII lines. For this purpose, the wings of the cloud intensity profiles along the magnetic field have been fitted with an exponential function. Measured λ profiles for the W7-AS shot #43580 ($n_e(0) = 6.2\cdot10^{13}$ cm^{-3}, $T_e(0) = 1.4$ keV, $P_{ECRH} = 410$ kW, $d_p = 0.4$ mm, $v_p \approx 300$ m/s) are shown in Fig. 2 by the solid line (scheme (1)) and triangles (scheme (2)). The longitudinal CII cloud decay length values have an order of several millimeters. The CII ionization length as the sum of ionization lengths for neutrals and the first carbon ions was calculated using the ionization cross-sections of Ref. [6] and the T_e, N_e profiles of ambient plasma. The cloud velocity was taken as the sonic speed with cloud

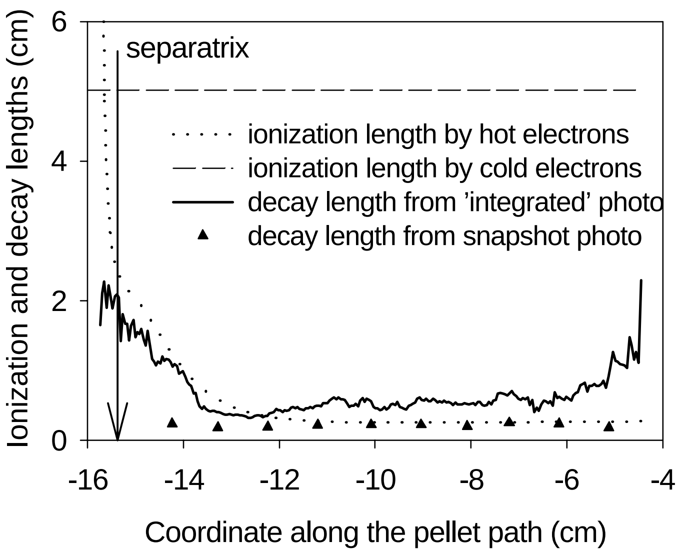

Fig.2. Cloud decay length and ionization length profiles for W7-AS shot #43580.

plasma temperature $T_{cl} \approx 1$ eV that could be derived from simulation results of carbon pellet cloud parameters in W7-AS plasma [7]. The calculated CII ionization length profile is shown in Fig. 2 by the dotted line. The ionization length values agree rather well with the cloud decay length values. In the quasi-3D pellet ablation code [7], only ionization by cold cloud electrons is considered in the pellet cloud. The dashed line in Fig. 2 shows evaluation of the CII ionization length by cold cloud electrons with maximum carbon pellet cloud parameters T_{cl} = 3 eV and $n_{cl} = 3{\cdot}10^{16}$ cm^{-3} simulated in Ref. [7]. This ionization length due to cold cloud electrons is substantially greater then the decay length λ measured in experiment and those calculated for ambient plasma electrons. It suggests that an influence of the cold ($T_{cl} \leq 3$ eV) cloud electrons on the ablatant ionization might be negligible. However, we should note that the role of cold electrons in the cloud ionization essentially depends on the T_{cl} values. For instance, for T_{cl} =4-5 eV and $n_{cl} = 3{\cdot}10^{16}$ cm^{-3} the CII ionization length by cold cloud electrons becomes comparable or even less then decay length values measured in experiment.

Summary. The structure of carbon pellet ablation CII clouds in W7-AS experiments has been studied. The cloud longitudinal decay length values (of order of several millimeters) generally agree with those calculated assuming the ionization of carbon cloud ablatant by hot plasma electrons. Snapshots of the CII clouds reveal a radial cloud asymmetry that is likely due to a radial cloud drift in plasma center direction with velocities of about 1 km/sec.

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