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Observation of cryogenic hydrogen pellet cloud distribution in ASDEX Upgrade plasmas

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Introduction

In order to get deeper insight into the physics of pellet ablation, cloud dynamics and interplay between plasmoid drift and penetration depth, detailed modelling is required. To verify the results of the theoretical models, observation of the 3D pellet trajectory, the pellet velocity and the distribution of the ablation cloud is indispensable with good spatio-temporal resolution. In the past the pellet cloud distribution was measured with CCD cameras and the pellet trajectory with position sensitive detectors or photomultiplier arrays [1,2,3,4]. To detect all the above quantities during cryogenic hydrogen pellet ablation in ASDEX Upgrade plasmas (torus radius 1.65m, minor radius 0.5m, plasma volume 13m^3) an observation system using fast digital cameras was developed and taken into operation. In this paper results obtained with this observation system are presented and discussed.

Experimental set-up

A tangential and a vertical view of the inboard pellet injection of ASDEX Upgrade tokamak [5] are combined onto one image using image guides and edged mirror. This image is simultaneously detected by three digital cameras (PCO SensiCam) with 12 bit dynamic range and an optical imaging system of beam splitters and lenses. This setup allows us to apply different timing and wavelength selections: every camera is capable to detect images of the pellet cloud from the two observation directions with a time resolution of a few μs. Both the exposure time of the images and the delay of the cameras can be as short as $1\mu s$ and multiple exposure mode operation is possible. The maximum frame rate is about 8 Hz. During the measurements presented here no wavelength selection was made therefore atomic line radiation of the pellet cloud is dominant.

The pellet injection system on ASDEX Upgrade consists of a centrifuge accelerator equipped with a storage cryostat type pellet source and a pellet transfer system for HFS (high field side) pellet injection [5]. The system is capable to deliver pellets of three different pellet sizes (cubes of 1.4, 1.65, 1.9 mm side length, i.e. nominal pellet mass $1.6, 2.7, 4.1 \times 10^{20}$ D-atoms) within a speed range of [240m/s, 1200m/s]. The repetition rate of the injection can be up to 100 Hz with maximum 120 single pellets in one train.

Pellet trajectory and velocity reconstruction

During the first operation phase of the observation system using long exposure times (covering the full pellet lifetime) penetration of 1000 m/s fast pellets 22 cm deep into the plasma was detected. Simultaneously, short times multiple exposures proved still intact pellets were delivered by the optimised transfer system [5].

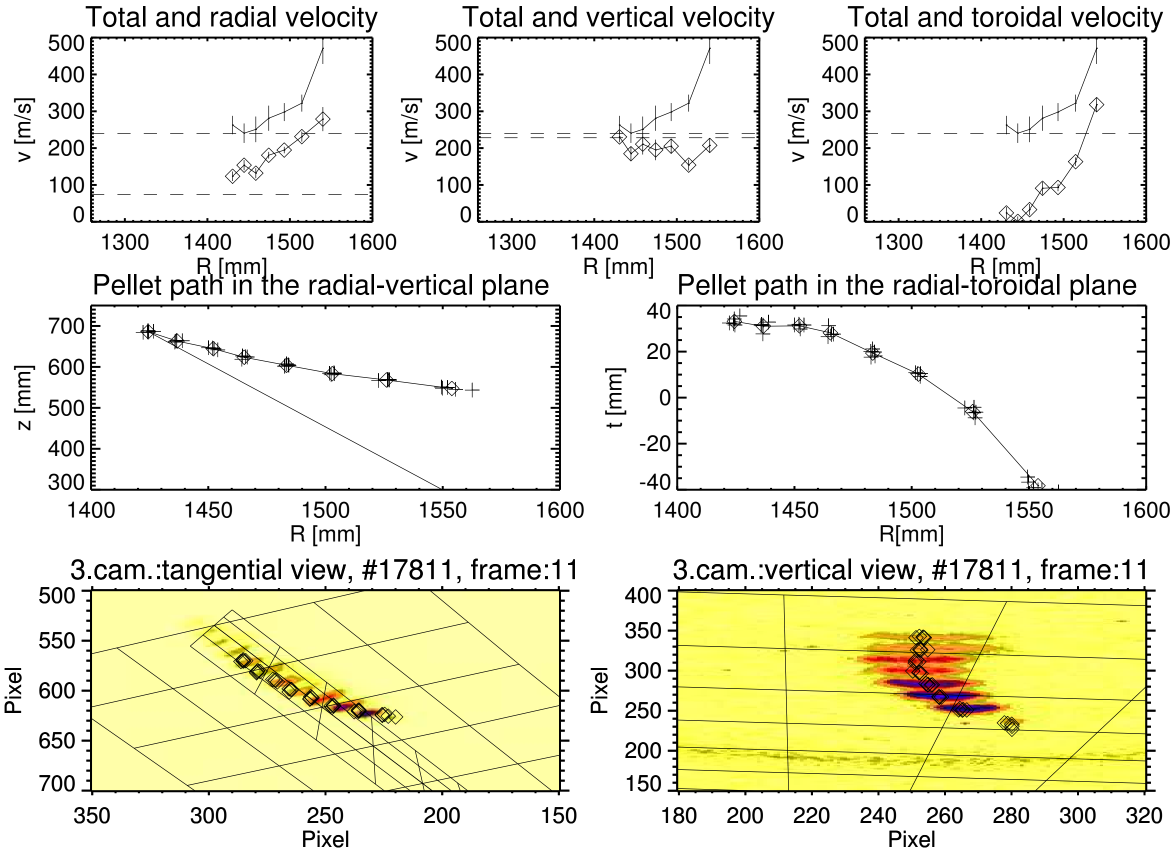

Figure 1: *Pellet acceleration during its ablation in the plasma.*

Taking into account both observation views and applying the spatial calibration of the detection system components of the 3D pellet trajectory, all pellet velocity components can be reconstructed from the images obtained in multiple exposure mode operation by using a minimisation method. To observe a clear effect of the pellet acceleration expected during ablation in the plasma [2] pellets as slow as 240 m/s were injected. For the analysis presented, the pellets were injected in a late phase of a discharge performed essentially for other investigations. Stable configurations were chosen known as reliable and tracktable, typical parameters where $I_P = 1MA$, $B_t = -2.4T$, $q_{95} = 4.5$, $\kappa = 1.8$, $\delta^u = 0.12$ and $\delta^l = 0.41$. Besides ohmic plasma heating, a moderate auxiliary heating power of 4 MW neutral beam injection (NBI) was applied to drive the plasma well into the type-I ELM H-mode regime and to allow the pellets penetrate deep into the plasma.

In the lower part of Fig. 1 poloidal and vertical views of the ablation region are plotted. Note that the vertical view is limited by mechanical parts of the observation port therefore the outer region of the pellet path is masked. Superimposed are two meshes of 100 mm x 100 mm square: one in the poloidal plane of the pellet injection and tilted parallel to the designated pellet line (inclination angle of 72°) and the other perpendicular to the previous one. The coordinates of the points marked with symbols are calculated and plotted in the middle part of Fig. 1. A line with a 72° inclination angle starting at the first reconstructed point is also seen in the figure of the radial-vertical plane. In the upper part of the figure the calculated velocities are shown. The horizontal dashed lines represent the initial values of the total velocity and the plotted component, respectively.

Clear acceleration of the pellet can be seen for both figures in radial and toroidal direction. The vertical velocity component remains almost constant. The same acceleration was detected with faster pellets (560 m/s). The radial acceleration is in the order of $10^5 m/s^2$ and in good agreement with values measured earlier [2]. The toroidal acceleration is somewhat larger.

The most likely explanation for this acceleration is a rocket effect caused by the asymmetric heating of the pellet surface. The toroidal acceleration is probably the consequence of different heat fluxes reaching the pellet surface on the electron and ion drift side. For HFS pellet launching the diamagnetic pellet cloud drifts in the inhomogeneous magnetic field overtaking the pellet. This leads to an enhanced shielding on the LFS of the pellet and a reduced one on the other side which accelerates the pellet towards the LFS.

Distribution of the pellet cloud

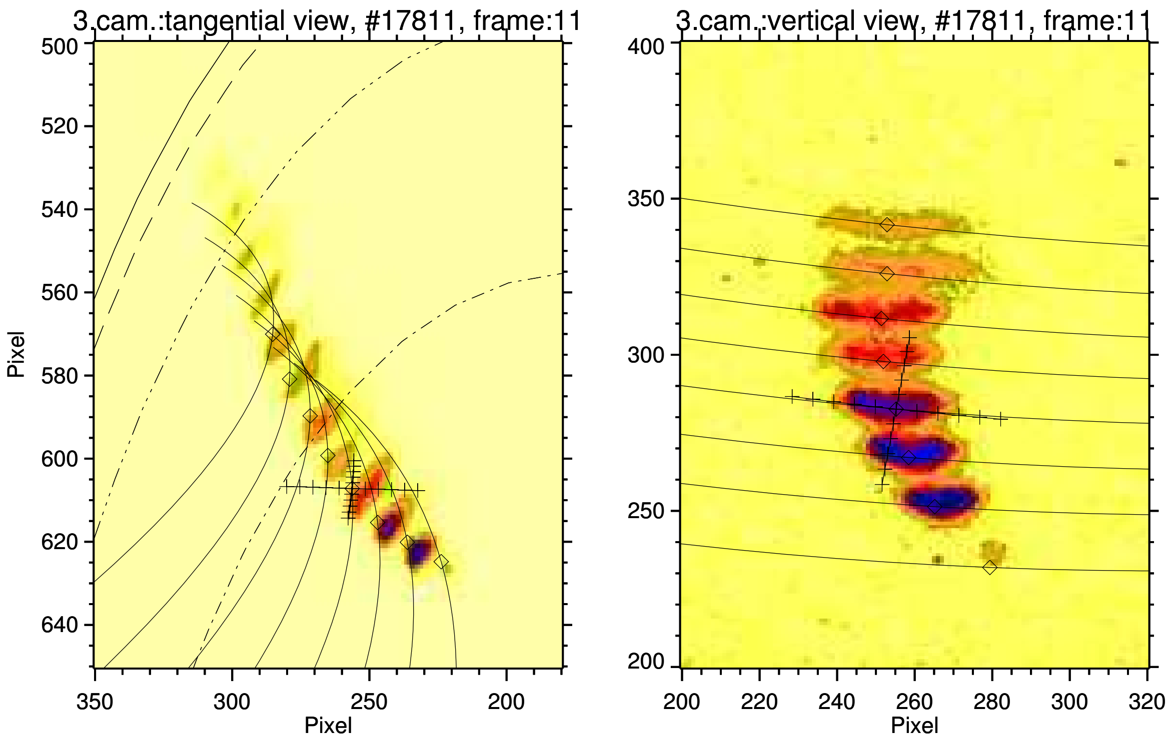

Figure 2: *The detected distribution of the pellet cloud along the pellet trajectory.*

In Fig. 2 the previously presented pellet's cloud radiation is delineated. The reconstructed pellet trajectory is superimposed in both views ($\diamond$). The traced magnetic field lines crossing these points are represented by the solid lines crossing the trajectory points. On the tangential view the solid curve on the upper left side represents for the separatrix in the poloidal plane of the pellet injection. The dashed and dotted curves illustrate the magnetic surfaces of q=5,4 and 3, respectively. A radial and toroidal scale of 1cm is delineated on both view, too.

The pellet cloud elongation along the field lines becomes visible in such figures. From the vertical view image it turned out that the cloud extends about 5-7 cm along field lines and has radius of 1 cm in both perpendicular directions. Investigating images of individual clouds on the tangential view we are facing a more complicated structure. Here, pellet cloud elongation along field lines is also visible (structure of the clouds parallel to the field lines) but with a lower resolution due to the small angle between the view direction and field line orientation. The toroidal cloud extension agrees well with the one measured using the vertical view. For most clouds in this figure a cloud extention in the poloidal direction can be seen as well,but only in clockwise direction. This elongation cannot be explained by the size of the cloud perpendicular to the magnetic field. This elongation may be seen on the vertical view, too: the cloud has not completely elongated along the field line, but has a slight v shape.

Summary

The full 3D pellet trajectory and velocity distribution was reconstructed from images of tangential and vertical view. The pellet cloud distribution was related to peculiar structures of the plasma. It is confirmed that the pellet is accelerated both toroidally and radially, probably caused by a rocket effect due to asymmetric heating. Furthermore, a poloidal elongation or drift of the cloud was observed which origin is not clear yet.

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