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Investigation of cryogenic pellet cloud dynamics

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In order to get deeper insight into the physics of pellet ablation, cloud dynamics and interplay between plasmoid drift and penetration depth hydrodynamical codes are developed. Recent codes assume that the ablating pellet periodically crosses its shielding cloud, fueling a series of flux tubes along the pellet path [1]. Additionally, experiments revealed that the pellet cloud drifts towards the low field side of the torus [2]. Therefore the investigation of the cloud dynamics with high spatio-temporal resolution is needed.

To detect the spatial distribution and time evolution of the radiation emitted during pellet ablation in ASDEX Upgrade plasmas a fast camera observation system [3] was used. The setup (Fig. 1) consists of three fast, triggerable digital cameras with 12 bit dynamic range and an optical imaging system. The inboard injected pellets are observed from two different directions. A side view mounted in the next octant of the torus observes the whole poloidal cross-section of the inboard pellet injection and a top view was mounted at the cross-section of the pellet injection. These two views were combined onto one image, therefore all three cameras are capable to detect images of the pellet cloud from the two observation directions simultaneously: both the exposure time of the images and the delay between the cameras can be as short as $1\mu s$. For these investigations the cameras were run in the multiple exposure mode that is several $5\mu s$ exposures were made with $100\mu s$ repetition time onto the same frame. To make the spatio-temporal cross calibration of the three cameras, images were made with same timing. To detect the rapid changes of the pellet cloud distribution the 2nd and 3rd cameras were delayed relative to the first one (a) in the first experimental series with 3 and 6 μs and (b) in the second series with 5 and $10\mu s$, respectively.

The timing of the cameras was tested with a LED array (the diodes blink in a sequence which enables determination of camera exposure start time and length relative to the start trigger) and it was found that the jitter time of cameras is less than 1 μs. The spatial cross calibration of the images of the different cameras is better than 5mm.

Images were made of the pellet clouds using different interference filters in front of the cameras. We found no difference on images made with H_α filter (656.7nm, 2.9nm FWHM) and without filter. An attempt was made to detect radiation due to bremsstrahlung and recombination of the cloud particles (filter: 538.3 nm, 2.8nm FWHM) but the sensitivity of the imaging system was not enough to detect any radiation. Therefore in the investigations described here no filters were used.

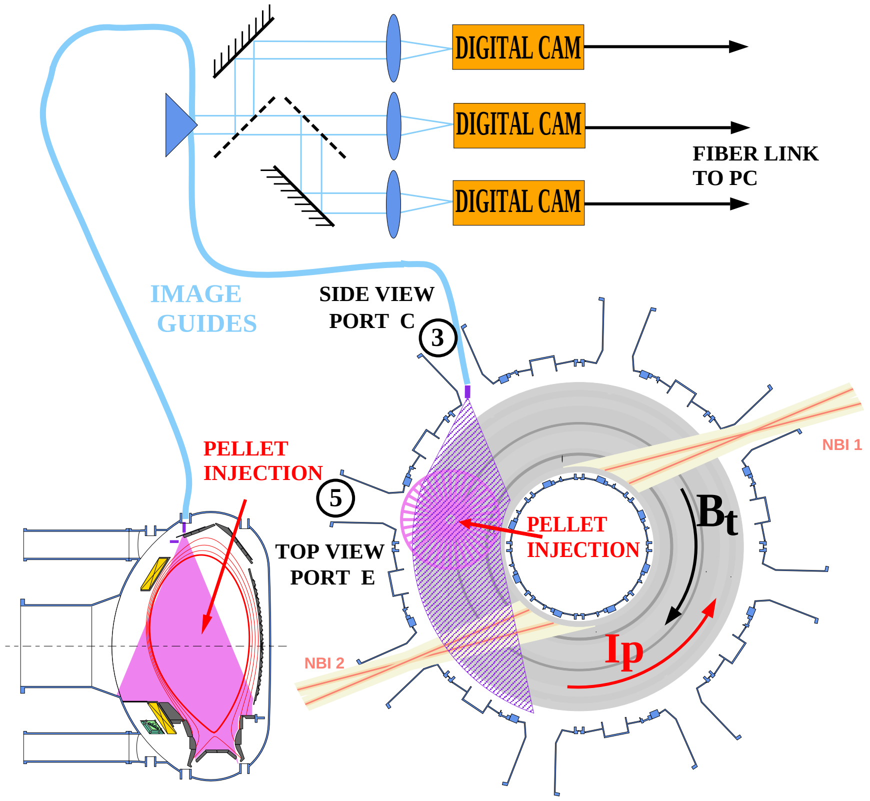

Figure 1: *Fast camera system for pellet observation on ASDEX Upgrade.*

Our previous investigations showed that the pellets - injected from the high field side (HFS) of ASDEX Upgrade into the plasma - are accelerated in the radial direction to the low field side (LFS) [3] resulting in a curved pellet path. This acceleration is probably caused by a rocket effect due to asymmetric shielding of the pellet which is the consequence of the ∇B induced outward drift [4] of the pellet cloud. Recently pellets were injected into reversed magnetic field discharges and the same curvature of the pellet path was observed. This observation confirms the above explanation because the direction of the ∇B induced drift is independent of the reversal of the magnetic field.

Fig. 2 shows side view images of one deuterium pellet (240m/s, 1.9x1.9x2.0 mm^3) observed by three cameras with 0,3,6 μs delay, respectively. Stable discharge conditions were chosen with typical parameters e.g. $I_P = 1MA$, $B_t = -2.4T$, $q_{95} = 4.5$, $\kappa = 1.8$,

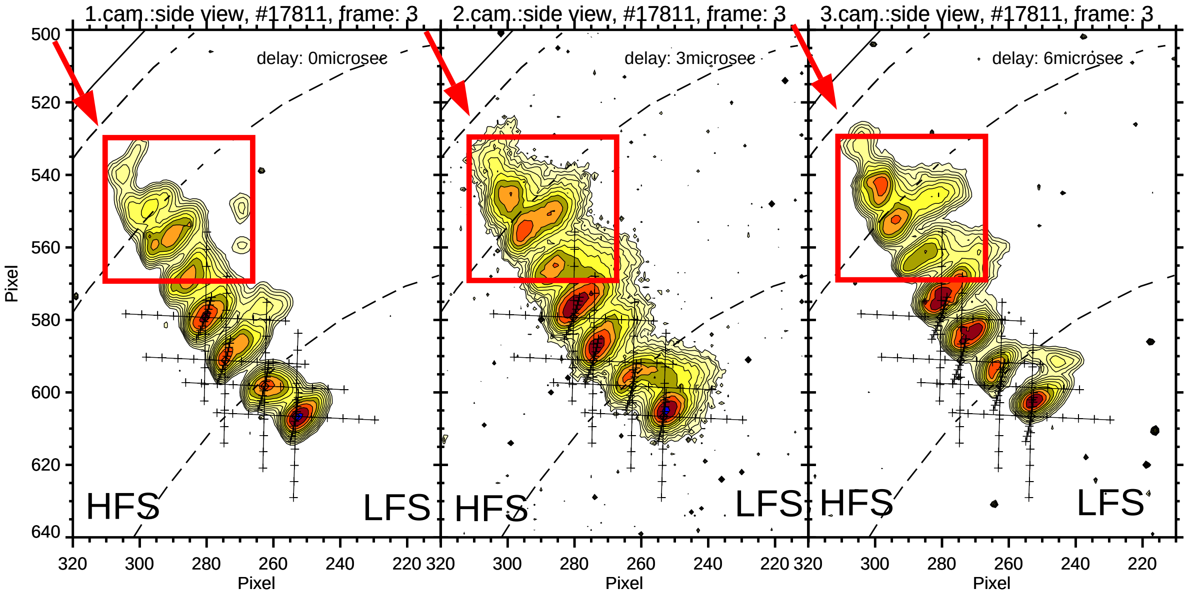

Figure 2: *Multiple short exposure side view images of a deuterium pellet (240m/s, 1.9x1.9x2.0 mm*^{3}*) observed by three cameras with 0,3,6 µs delay, respectively. The solid and dashed curves illustrate the separatrix and magnetic surfaces of q=5,4 and 3. The major radius increases from left to right. The red arrow symbolizes the direction of the pellet injection. Radial(horizontal), vertical and toroidal scales of 1cm per tick are delineated at reconstructed points of the pellet trajectory.*

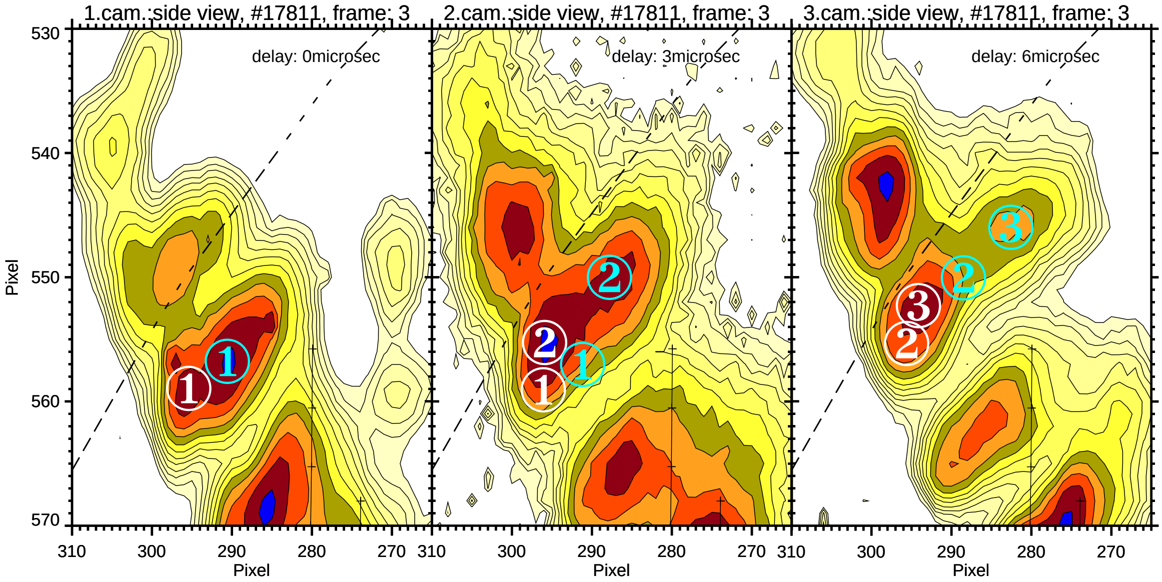

Figure 3: *Magnified parts of the previous figure (marked with red square). The white and blue numbers represent position of two selected local maxima seen on successive images.*

$\delta^u = 0.12$ and $\delta^l = 0.41$. Besides ohmic plasma heating, a moderate auxiliary heating power of 6.8 MW neutral beam injection (NBI) was applied to drive the plasma well into the type-I ELMy H-mode regime and to allow the pellets to penetrate deep into the plasma. The individual patches along the pellet path (pellet injection marked with red arrow) represent distribution of the pellet cloud radiation at different moments (separated by 100 μs) during the ablation. It is clear that on all three camera images (that is independently of the delay time) the clouds have a clear maximum and sometimes the cloud is elongated in poloidal direction, but always clockwise. This elongation changes rapidly in time, the elongated cloud part can appear or disappear in $6\mu s$. To see more details one magnified cloud is shown on Fig. 3 as seen by the three cameras with $3\mu s$ relative time delay. The movement(time evolution) of two typical points of the distribution is marked with white and blue numbers, respectively (e.g. the position of point 1 is marked with white number 1 at $0\mu s$ delay time, with white number 2 at $3\mu s$ delay time and with white number 3 at $6\mu s$ delay time). To visualize the movement of this points the previous position are delineated also on the figure at the next moment. We think that the peak marked with white numbers is the main cloud which essentially shields the pellet. It moves vertically upward about 1 cm in this $6\mu s$. This kind of clouds moves typically upward in this discharge (see also Fig. 2). This vertical displacement was already discovered at LFS pellets injection [5], but its origin is not clear yet. The cloud part marked with blue numbers is related to the drifting plasmoid which posteriorly detaches from the primary cloud. It moves both in the radial (to LFS) and vertical direction (upward) covering a distance of a few cm in $6\mu s$.

From experiments with longer delays between cameras(series b) it can be concluded that the drifting cloud is visible/detectable for $10\mu s$ in our present observation system. In this period the drifting cloud becomes completely detached moving poloidally (clockwise) a few cm distance.

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