Investigating pellet ablation dynamics at ASDEX Upgrade

G. Kocsis[1], L. Barrera[2], J.E. Boom[3], T. Craciunescu[4], G. Cseh[1], P.T. Lang[2], N.C. Luhmann Jr[5], G. Náfrádi[6], H.K. Park[7], T. Szepesi[1] and ASDEX Upgrade Team

[1]*WIGNER RCP, RMKI, EURATOM Association, POB 49, 1525 Budapest, Hungary*

[2]*MPI für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany*

[3]*FOM Institute DIFFER, Association EURATOM/FOM, The Netherlands*

[4] *EURATOM-MEdC Association, Institute for Laser, Plasma and Radiation Physics Bucharest, Romania*

[5]*Department of Electrical and Computer Engineering, University of California at Davis, Davis, CA 95616, USA*

[6]*Department of Nuclear Techniques, BME, Association EURATOM, H-1111 Budapest, Hungary*

[7]*POSTECH, Pohang, Gyeongbuk, 790-784, Korea*

1. Introduction. Cryogenic pellet injection is one of the prime candidates to fuel large scale fusion devices - like ITER and DEMO - in different operational regimes. Moreover, cryogenic pellet injection is also a promising tool to control Edge Localised Modes (ELMs) associated with the standard H-mode foreseen as ITER`s baseline scenario. To allow for an efficient use of the pellet injection tool, the predictive understanding of the underlying processes of the pellet-plasma interaction is indispensable. Recent investigations supported the assumption that pellet ablation is a complex 3D process taking place on the μs timescale, involving - among others - pellet cloud dynamics (expansion, instabilities and drifts) and the fast axisymmetric plasma cooling.

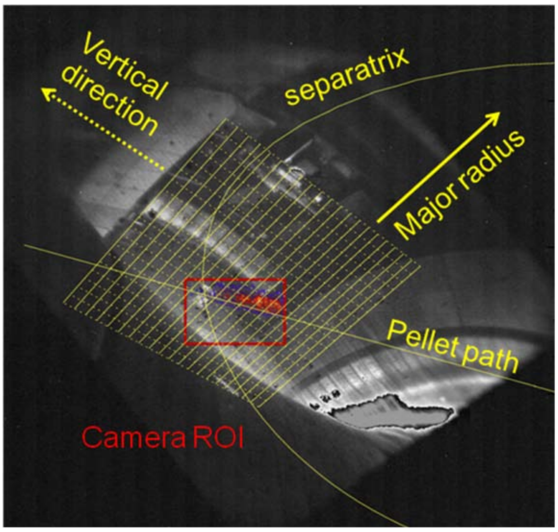

Fig.1. The tangential view of the fast framing camera (for the details see the text).

2.Experiment. Recently developed diagnostics at ASDEX Ugrade open powerful new possibilities to investigate pellet ablation dynamics and the pellet-caused target plasma cooling on a time scale fast enough to resolve the pellet motion (the pellet moves less than its initial diameter within 1μs). The fast framing pellet video system [1] was upgraded with a Photron SA5 CMOS camera with a frame rate up to 1MHz. The typical tangential view of the camera used in these investigations is seen of Fig.1. together with the radial (solid lines) - vertical (dashed lines) mesh. To be able to run the camera at 350kfps a small region of interest is recorded (red frame on Fig.1. The ECEI temperature measurement [2] is located around the outer mid plane toroidally 90 degree (anticlockwise) from the pellet injection cross-section. Its time resolution is up to 1MHz. The flexible inboard pellet launching system [3], injecting pellets with different size, speed and repetition frequency, is also well suitable for such studies at ASDEX Upgrade.

Experiments summarised in this contribution were performed during the 2011 campaign of ASDEX Upgrade (v_{pellet}=560m/s). As target discharges H-mode with n=2 magnetic perturbation which suppresses type-I ELMs [4] were selected. This way the complication of type-I ELMs on the pellet ablation is avoided but as a consequence of the magnetic perturbation the field lines at plasma periphery may leave the unperturbed magnetic surfaces.

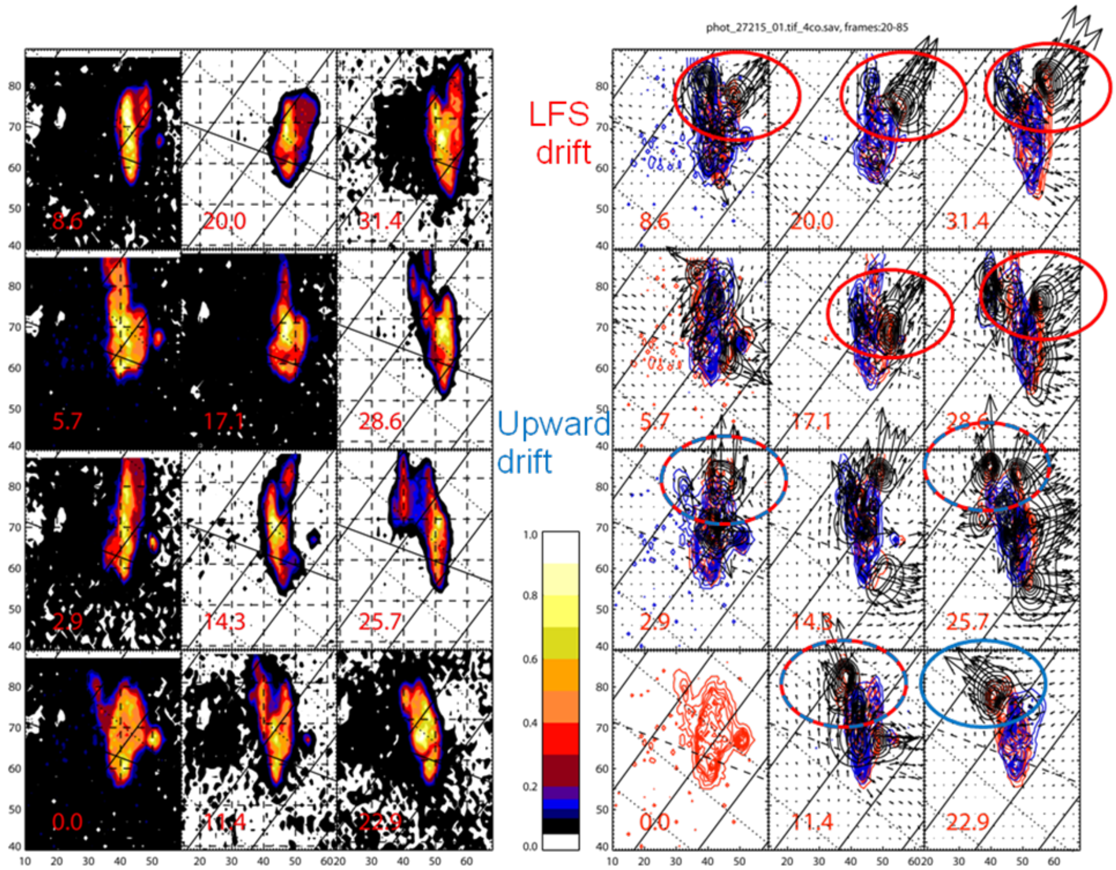

Fig.2. Snapshots of a 350kfps movie about an ablating pellet (on the left) together with the result of the optical flow method calculation (right). See main text for details.

3. Investigation of pellet ablation cloud movement. The main emphasis is put on the analysis of pellet cloud dynamics and drifts by observing the visible radiation with the fast camera and by applying image processing algorithms. Snapshots of a typical 350kfps movie can be seen on the left part of Fig.2. The time elapses from down to up and from left to right. The overplotted mesh and designated pellet trajectory is the same as on Fig. 1. Having a closer look to such movies it was observed that the pellet and its cloud move together through the plasma with the pellet injection speed on the µs time scale as well. Contradicting to earlier modelling approaches no “flux tube fuelling”, that is, jumping from one flux tube to the next one was recognised. During penetration parts of the main ablation cloud, localised around the pellet, are regularly erupted. These attached cloudlets move typically to the outward radial direction with a velocity much higher than the pellet speed. This movement could be associated with a grad B caused pellet cloud drift. Sometimes the erupted cloudlet moves in the upward vertical direction; the explanation of this finding is not yet clear. As a possible consequence of the cloudlet eruption, the shape of the pellet cloud and therefore the radiation pattern detected by both radial and tangential viewing cameras changes on a fast time scale.

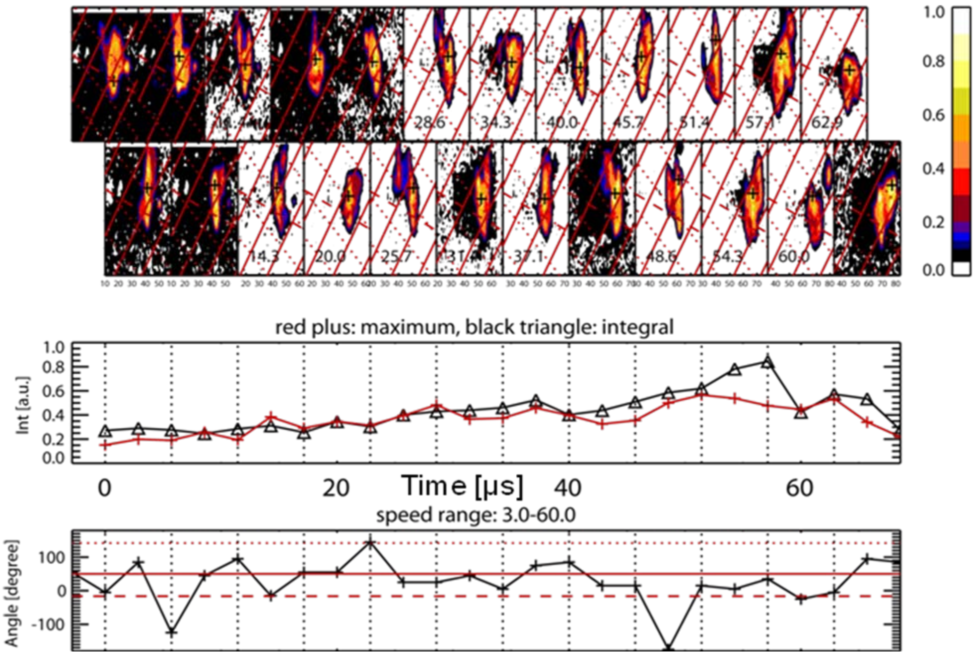

Fig.3. Time evolution of single parameters calculated for each frames (for details see text).

To characterise the evolution and the movement of the pellet cloud seen on the fast movies, the snapshots were evaluated by applying the optical flow method [5], and the resulting velocity field is plotted on the right of Fig.2 as black arrows (the arrow length is proportional to the velocity). Here the snapshot frames are also plotted (red contours) and also the previous ones (blue contours) - these were used to calculate the optical flow velocity field. It can be easily concluded, that the speed of the drifting cloudlets are much larger than any other speed calculated, exceeding 2000 m/s. The optical flow method can clearly recognise the drifting cloudlets and the above mentioned two typical directions (from HFS to LFS - highlighted by red ellipses -, and upward motion - blue ellipses). We wanted to characterise each optical flow velocity frame with one value, therefore the histogram of the velocity direction was calculated for each frame, and it was seen that it has a clear, narrow maximum which mostly reflects the drifting cloud. On Fig.3 such "single" values calculated from each frames are plotted as a function of time. The upper part of Fig.3 shows the frames of the movie. The lower part is the above described most probable direction of the velocity, where the red solid line is the direction from HFS to LFS, the dotted line is the upward direction and the dashed line is the pellet flight direction. It is clearly seen that the most probable direction is always between these angles. The middle curve on Fig.3 shows the time evolution of the total radiation of a frame (black curve) - which is typically detected by wide angle view pellet monitor diagnostics - and the maximum radiation (red curve). One can see that the total radiation has a local maximum if drifting cloudlets are also present and contribute to the radiation. This is in contradiction to earlier expectations that the fluctuating pellet cloud radiation has a minimum caused by the drop of the ablation.

4. Observation of the pellet caused plasma perturbation by ECEI. From earlier experiments it is known that a mm size cryogenic pellet instantaneously cools the plasma (the electron temperature drops by a few 10%) and the front of the target plasma cooling moves together with the pellet [6]. The cooling looks axisymmetric on the 30μs timescale but it is of interest to see if any poloidal asymmetry exists on the 5μs time scale. On the other hand the ablating deuterium pellet deposited particles form a dense cloud elongated along a magnetic field line and distributed on the whole magnetic surface at least one order of magnitude slower than the cooling effect. This way the target plasma density is remarkably increased and can reach the cut-off density for the ECEI measurement. Here we can expect first a poloidally localised cut-off when the pellet cloud filament reaches the ECEI observation volume.

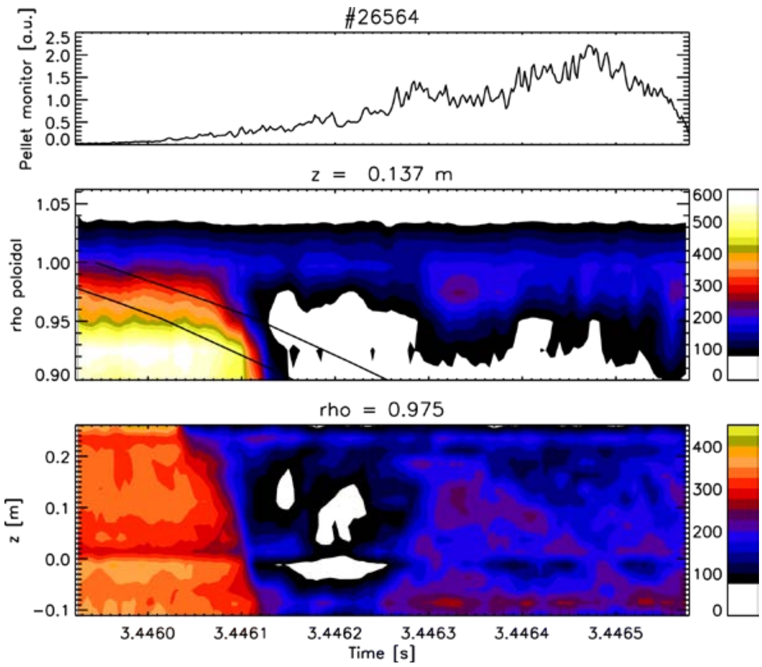

Fig. 4. Time evolution of pellet ablation, the radial (at vertical coordinate z=0.137m) and the vertical (at poloidal flux=0.975) distribution of the ECEI plasma temperature. For ECEI measurements below 100eV, the plasma is either in cut-off (inside the separatrix) or it is optically thin (outside the separatrix). In both cases, the measurement is no longer directly related to Te.

The typical time evolution of the ECEI measured temperature distribution during pellet ablation is plotted on Fig.4. The upper plot shows the pellet ablation monitor. The middle and the lower one the radial and the poloidal distribution of the electron temperature. The pellet location is expected between the black curves seen on the middle plot. It is clearly seen the pellet caused density increase causes a measurement cut-off after t=3.44608s. The cut-off appears poloidally asymmetric, it starts first at the upper part of the observation volume (z=0.2) and moves downward and shows up about 40μs later at z=-0.1. The reason of this asymmetry is not yet clear, a field line tracing of the pellet cloud filament does not explain it. Before the cut-off the ECEI can also detect the pellet caused cooling (see e.g. the middle plot after t=3.44605, where orange coloured layer - ~350eV - moves deeper into plasma together with the pellet). These behaviours will be further investigated in the future using smaller/faster pellets to cause less density perturbation of the plasma.

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