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The effect of pellet size on the pellet cloud distribution and radiation

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Introduction. Pellets of various materials are injected into thermonuclear fusion devices for different purposes. Hydrogen isotope pellets serve for refuelling the plasma or for tailoring the density profile [1] while impurity pellets are used either for radiative cooling of the plasma edge or to quench the plasma ('killer pellets') prior to hard disruptions or for diagnostic purposes [2]. In the description of pellet-plasma interaction there are a few unsolved cardinal phenomena such as the distribution of the cloud around the pellet or the radiation of the cloud particles. Our earlier experiments [3] have shown that micro-pellets interacting with hot plasma exhibit similar features to that of millimetre size pellets. If we assume that the plasma-pellet interaction is governed by the same physical processes for both micrometer and millimetre size pellets – although the shielding of the pellet cloud is almost negligible for micro-pellets – then the results of micro-pellet experiments can help in the interpretation of various phenomena seen in experiments with millimetre size pellets. In this paper we present the results of our systematic investigations to measure the distribution of atoms and ions in the pellet cloud for different pellet sizes.

Experimental set-up. Laser accelerated aluminium micro-pellets of different sizes (equivalent radius (r_{eq}) varies between 7-30 μm) were injected into MT-1M and TEXTOR-94 tokamak plasmas. On MT-1M tokamak the injection was done from the bottom and on TEXTOR-94 from the top, in both cases along a vertical central chord. The intensity and spatial distribution of the line radiation of the first three charge states of aluminium (Al I: 3944Å, Al II: 6243Å, Al III: 5697Å) in the pellet cloud were observed with a gateable CCD camera through a side port on the low field side on both tokamaks. On MT-1M a PCO FlashCam (8 bits resolution) and on TEXTOR-94 a PCO SensiCam (12 bits resolution) were used. The cameras are used in two different modes: to analyse the light emission during the whole ablation, long exposure (4-5ms) "integrated" images were taken on MT-1M tokamak. To learn about the short time feature of the cloud distribution, 1μs exposure time "snapshot" images were taken on TEXTOR-94 and MT-1M tokamaks.

Experiments. On long exposure images observed with Al III filter clear magnetic field aligned structures (striations) are seen for all pellet sizes, which are more enhanced for smaller pellets (r_{eq}=7,10,13,15μm). The light intensity distributions along the magnetic field lines are different for smaller and larger pellets: for smaller pellets it is broader while for large pellets it is narrower. These differences can be better seen on 1μs snapshot images that reveal a more detailed characteristics of the intensity distributions (see Fig.1).

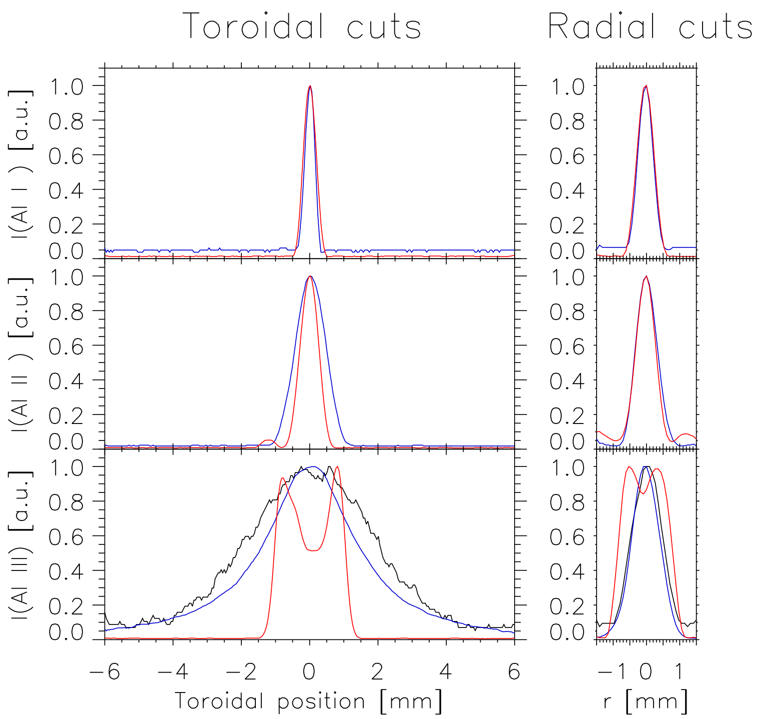

Figure 1: *Toroidal and radial cuts of 1μs images for pellets with equivalent radius of 11μm (black lines), 16μm (blue lines) and 28μm (red lines) made on MT-1M tokamak. The upper curves are observed with Al I (r_{eq}=16,28μm), the middle ones with Al II (r_{eq}=16,28μm) and the lower ones with Al III (r_{eq}=11,16,28μm) filters. The velocity of the individual pellets varies between 320$\frac{m}{s}$ and 520$\frac{m}{s}$.*

Our observations show (see Fig.1) that the Al I radiation is localised close to the pellet and has a peaked, nearly circularly symmetric distribution for all pellet sizes. The Al II radiation has a similar distribution, but for smaller pellets it is slightly elongated along the magnetic field lines. The Al III radiation distribution was also peaked but toroidally much broader for small pellets. It had a hollow profile in both directions for large pellets and the diameter of the 'crater' was typically around 1mm. The radial size of these radiation distributions did not vary significantly for the different pellet sizes.

To explain this behaviour one can speculate as follows. Close to the pellet - where the density is high - the electrons emerging from the ionisation of ablated material determine the evolution of the cloud. In the case of the micro–pellets the shielding of the pellet cloud is small, therefore the ablation rate is proportional to the pellet surface. For small pellets the ablation rate is small, which results in low cloud and hence electron density. In this case the ions have a lifetime long enough and can travel to a considerable distance along the flux tube. For larger pellets, the ablation rate and hence the cloud electron density is higher and the ions have a shorter lifetime, therefore the toroidal distribution is narrower.

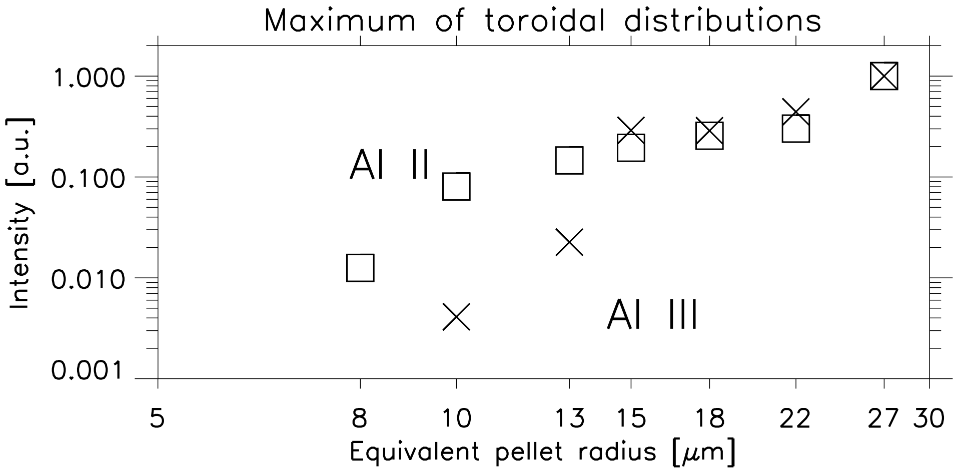

Figure 2: *The maximum values of the toroidal distribution of Al II (□) and Al III (×) line intensities as a function of the equivalent pellet radius. The values were obtained from "integrated" images averaged over the radial range of [-35,-40]mm taken on the MT-1M tokamak. Both curves are normalised to one.*

On Fig.2 the maximum values of the toroidal distribution – averaged over the radial range of [-35,-40]mm – of Al II and Al III line intensities are plotted as a function of the equivalent pellet radius. Both curves exhibit a nonlinear behaviour and the Al III line radiation drops faster with decreasing pellet radius. This drop is so fast that the Al III radiation of the smallest pellets was not detectable by the camera.

Micro-pellets were injected into both ohmic and NBI heated TEXTOR-94 plasmas and multiple exposure images of the distribution of Al III line radiation were taken. An example for an ohmic discharge with line averaged density of $2.7{\cdot}10^{19} m^{-3}$ is shown on Fig.3. Two pellets were detected (r_{eq}=$30\mu m$): one (v=$660\frac{m}{s}$) at 6mm and the second (v=$320\frac{m}{s}$) at 10.5mm toroidal position. It is clearly seen here that – due to increasing electron temperature and density – the toroidal extension of the pellet cloud exhibits a shrinking trend as the pellet penetrates deeper into the plasma. (Keep in mind that – due to striations – the toroidal size of the cloud fluctuates.) Analysing the pictures made of pellets with different radii, the same general behaviour was seen as on MT-1M: smaller pellets have a wider cloud in the toroidal direction than the larger ones. For large pellets the distribution was not always hollow but mostly peaked. It was also detected that at higher temperature discharges (NBI heated) – due to higher ionisation rates in the cloud – the toroidal size of the Al III cloud was smaller than at lower temperature.

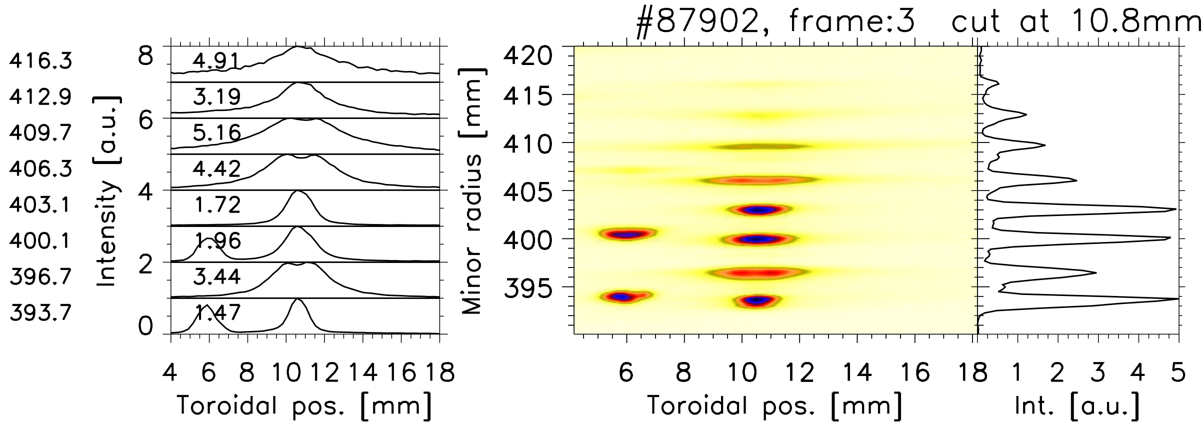

Figure 3: *Multiple exposure image of the Al III line radiation. A series of 1μs exposures with 100kHz repetition rate was made onto the same picture. On the right, a radial line cut at 10.8mm is depicted. On the left side, toroidal line cuts at the local maxima of this radial cut are shown. On each radial cut the FWHM of the distributions and the radial position of the cut (very left side) are printed in millimetre.*

Conclusions. Line radiation from ions and atoms of the aluminium micro-pellet cloud were detected with good temporal and spatial resolution on MT-1M and TEXTOR-94 tokamaks. The pellet cloud distribution and radiation was investigated systematically by varying the pellet size. Striations were found to be present in the Al III radiation for all pellet sizes. It was observed, that the line radiation of Al I and Al II was localised close to the pellet. The distribution of the Al III radiation was toroidally broad for smaller pellets and narrower and hollow for larger pellets. It was seen that the line radiation of Al II and Al III exhibits a different nonlinear dependence on pellet size.

To understand and explain the experimental observations a numerical simulation taking into account hydrodynamics and detailed atomic physics model would be necessary. Such a code is presently being developed [4].

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