Fast dust particles in tokamak plasmas: detection and effects

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It is known from 60s [1] that micron-sized dust particles with hypervelocities (of the order of 10 km/s) can have sufficient energy for impact ionization when colliding with solid surfaces. Dust detectors based on this phenomenon are widely employed in space research nowadays (see e.g. [2]). In tokamaks, the dust particles can be accelerated to such velocities due to different mechanisms. The ion drag can accelerate the dust up to ion flow velocities, which are typically of the order of tens of km/s for toroidal plasma flow near the last closed magnetic surface (LCMS). The acceleration could be even faster if resonant ion drag occurs [3] or if rocket force is taken into account [4]. Recently a new mechanism of dust acceleration based on stochastic heating was proposed [5]. If such fast particles exist in the scrape-off layer (SOL), dust impact ionization could be used as a diagnostic [6].

Here we briefly summarize evidence of dust impact ionization processes in SOL of FTU [7] which is a full metal machine, with a TZM Molybdenum alloy inner toroidal limiter, inconel or TZM poloidal limiter and stainless steel first wall. The experiment is performed in ohmic discharge with current $I_P = 0.36$ MA, line averaged plasma density $n_e = 4\ 10^{19}\ m^{-3}$ and magnetic field B = 7.1 T. UFOs were detected during several shots of the experimental campaign indicating that the appropriate conditions for dust study were chosen. Measurements of fluctuations of the ion saturation current were carried out by two molybdenum probes in the equatorial plane with poloidal separation of 0.6 cm. The probes were moved radially to "scan" the last centimeter near the wall.

A typical time series recorded by any of equatorial probes exhibits a high frequency turbulent part and a number of large spikes. Results of statistical analysis suggest that the large spikes (events) "seen" by the two probes are poorly correlated; the maximum of cross-correlation function is below 0.3, the cross-coherence is less than 0.3 for all frequencies. Fig. 1 presents results of conditionally averaged wave-forms measured by the two probes and shows that with a threshold of 4 rms the signal from the "unconditioned" probe signal is only a fraction of the big event seen by the conditioned probe. When the threshold is raised to 8 rms, the difference between signals on two probes is about one order of magnitude.

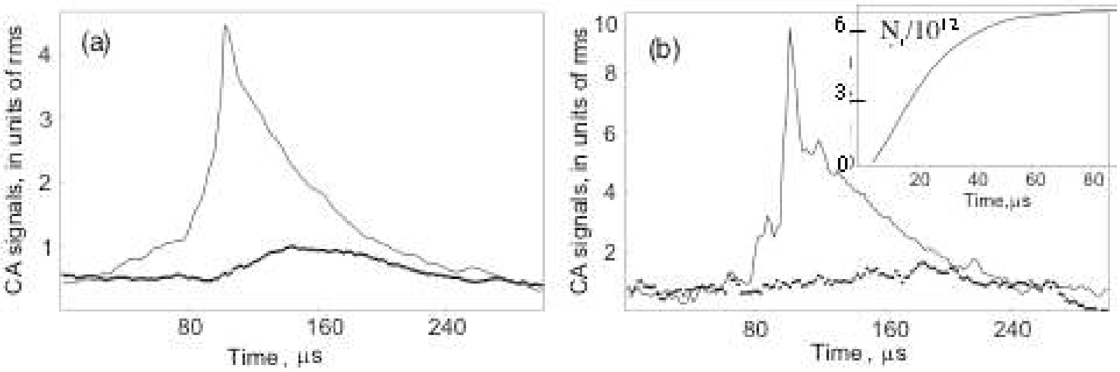

Fig.1: Conditional averaged signals of poloidally separated probes with threshold of 4 rms (a) and 8 rms (b). The thin curves are the CA-signal for the trigger probe. The insert shows the number of elementary charges collected by the probe during a typical large event [such as shown in (b)].

We could explain such a weak correlation by damping of the plasma structures ("blobs"). This, however, does not seem to be the case as the separation between the probes is 0.6 cm, the typical structures of edge turbulence are reported to be in excess of 1 cm (see e.g. [8-10]). Moreover, as seen from Fig.1 larger events are characterized by weaker correlation while higher amplitude plasma structures are expected to have longer poloidal correlation lengths, see e.g. Fig. 10 in Ref.[8]. Another evidence, which does not support interpretation of results in terms of "blobs", is that the event rate is actually increasing towards the wall (for example for largest events, above 8 rms, it changes from 20 to 80 Hz). And finally, we found out that characteristic decay time of the spikes does not depend on their amplitude and is a function of the probe radial position only. This is consistent with interpretation of such current spikes as collection of the ion clouds produced upon impacts of dust with probe. In fact, the number of elementary charges collected by the probe during a typical large event [such as shown in Fig.1(b) insert] is in good agreement with existing empirical formulas on hypervelocity micron size dust particle impacts [11].

Electron microscope analysis of the probe surface yielded direct support for such an interpretation. Fig.2 shows that the surface of the probe exposed to a plasma exhibits craters which are typical footprints of dust impacts [1]. No craters were observed on the "virgin" probe. Moreover, spherically shaped particles of a micron size with 80 % iron composition were found embedded in the surface of the exposed probe (see Fig.3). The probes were used only during one experimental day with total exposure to plasma of about 10 s. With rates of *largest* events cited above, we find that the total number of events is about equal to the number of craters found on the probe surface (about 500). The latter reflects only the number of largest craters, since for counting optical microscope was used.

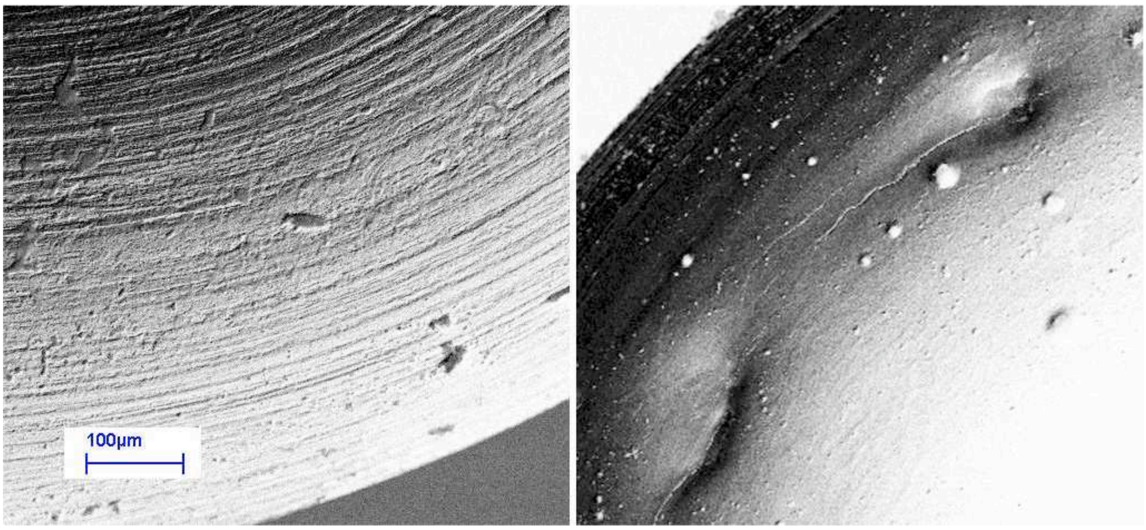

Fig.2: Electron microscope analysis of the surface of the unexposed probe (left) and probe used in the measurements (right).

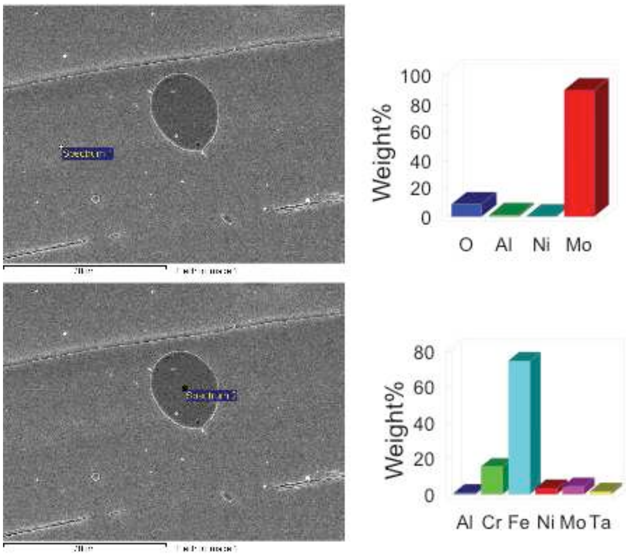

Fig. 3 Histogram of composition of a particle found on the surface of the probe exposed to the plasma

An important consequence of the presence of such fast dust particles is that when they impact the tokamak wall, the ejecta far exceed the projectile masses. This provides fresh particles as well as the release of neutral gas and plasma, "a runaway" process that could be a potential hazard for achieving sustained fusion conditions [12]. The contamination mass can grow exponentially at a huge rate (higher than 10 s^{-1}) [12] unless additional loss processes (e.g. melting, sputtering etc) reduce the secondary dust population considerably or unless acceleration to 10's of km/s is made impossible by a suitable reactor design.

The density n_{Fe} of iron contaminant ions in the main plasma, produced by the ionization of the Fe neutrals of the wall ejecta penetrating across the last closed magnetic surface, was evaluated in Ref.[12] from the balance with the ion diffusion towards the edges. With diffusion coefficient D =5 10^3 cm^2s^{-1} [13], $n_{Fe} \sim 10^9$ - 4 10^{10} cm^{-3} was found. In the considered FTU discharges the measured "intrinsic" Fe ion density in the core plasma was estimated as $n_{Fe} \sim 10^{10}$ cm^{-3}. This suggests that dust impact phenomenon could be an important contribution to the balance of the iron impurity.

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