Detection of Dust Particles in FTU

C. Castaldo 1), E. Giovannozzi 1), S. Ratynskaia 2), G. Capobianco 3), M. De Angeli 4), U. de Angelis 5), M. Kretschmer 6), G. Maddaluno 1), C. Marmolino 2), G.E. Morfill 6), V. Pericoli-Ridolfini 1), L. Pieroni1), K. Rypdal 7), A. Rufoloni 1), A.A. Tuccillo 1), A. Vannozzi 1)

1) Associazione Euratom-ENEA, Frascati, Italy
2) Association Euratom-VR, Royal Istitute of Technology, Stockholm, Sweden
3) Department STAT, University of Molise, Pesche (IS), Italy
4) Associazione Euratom-ENEA, IFP-CNR, Milano, Italy
5) Department of Physical Sciences, University of Naples and INFN sezione di Napoli, Italy
6) Max-Planck-Institut fur extraterrestrische Physik, Garching, Germany
7) Department of Physics and Technology, University of Tromso, Norway

e-mail contact of main author: castaldo@frascati.enea.it

Abstract. Results are reported of the ongoing investigations on dust particles present during FTU discharges and in the post disruption. A characterization of the dust component present in the FTU vacuum chamber has also been attempted by laser light elastic scattering on particles detected after disruptions. Special attention is given to development of in-situ dust detection. The latter includes a diagnostics based on the dust-impact ionization phenomenon which can be used for detection of particles with velocities above a 2-3 km/s as well as the use of aerogels, light porous materials, to capture dust particles without destroying them and dust detection by Thomson scattering.

A research activity in the field of dust in fusion devices has been initiated at FTU since 2005, in collaboration with the Max Planck Institute for Extraterrestrial Physics (MPE), Garching, the Royal Institute of Technology (KTH), Stockholm and the Unversities of Naples and Molise. These investigations have included both theoretical aspects of dusty plasma physics [1-2] as well as experiments in FTU and developments of novel dust diagnostics [3-6].

A relevant experimental result in the FTU is the discovery of clear signatures of hypervelocity impacts of dust particles on plasma facing components during plasma discharges [3], [4]. Hypervelocity regime occurs when the impact speed exceeds the speed of the compression waves both in the target and in the material, it typically corresponds to velocities above 2-3 km/s. The resulting pressure can reach 1 TPa and the temperature can be sufficient to cause vaporization and ionization of the material. This phenomenon of dust impact ionization is known since 1964 [7].

First evidence of hypervelocity impacts in FTU was found in plasma discharges at $B_T = 7.1$ T, $I_P = 0.36$ MA and line averaged plasma density $\overline{n}_e = 4 \times 10^{19}$ m^{-3}. The evidence was inferred from the analysis of the fluctuations of the ion saturation current collected by two molybdenum electrostatic probes. The probes were separated in the poloidal direction and located at the equatorial plane very close (0.2-0.8 cm) to the wall. Typical signal observed by the probes is shown in Fig. 1. The results of the analysis suggest that the characteristics of extreme very rare events (current spikes of amplitude ≥ 6 rms current fluctuations amplitude), such as their amplitude, duration, shape, occurrence probability and rate as function of the position with respect to the wall are not compatible with those typical ascribed to the plasma propagating structures, as summarized below.

These large fluctuations are indeed detected only by one probe at a time, whereas events of smaller amplitudes (< 4 rms) are detected by both probes and correlate wel each other. This observation contradicts the general expectation that higher amplitude plasma fluctuations have longer poloidal correlation lengths (as suggested by Fig. 10 in Ref. 8). Moreover, the probability distribution function of times between the successive large events shows an exponential form, with the same e-folding time (about 100 μs) found when the delay time is evaluated on a single probe, or when it is evaluated as the time between events detected by different probes. This evidence indicates statistical independence among events on the two probes, and the occurrence of a Poisson process, unlike for plasma structures, where a typical appearance time has been reported [9].

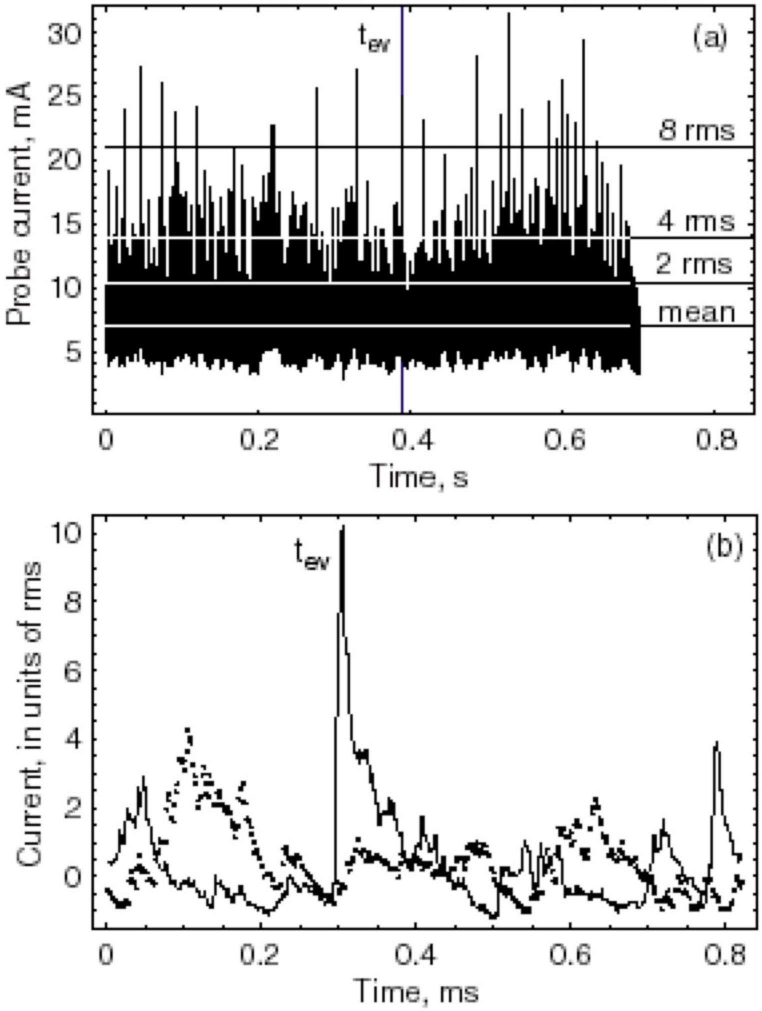

FIG. 1 - Ion saturation current signal with indicated levels of the mean value, 2, 4 and 8 rms (a). Zoom-in around the event selected on the above figure at the time t_{ev} (solid line) and the corresponding signal detected by the adjacent probe, poloidal separated by 6 mm (dashed line).

The events rate increases when the probe is closer to the wall. This contradicts what we would expect from assuming that extreme events are caused by propagating plasma structures thus suggesting the presence of a source near the wall.

These observations suggest that the current spikes detected by the probes are due to local phenomena, occurring at the surface of the probe. An interpretation of such spikes in terms of dust impact ionization by micron size iron particles impinging on the probe at velocity of the order of 10 km/s is consistent not only with the statistical considerations but also with the charge collected by the probes during the extreme events (10^{12} - 10^{13} elementary charges). The latter is confirmed by empirical formulas for hypervelocity dust impacts in vacuum, taking into account that, in a plasma environment, the charge produced should be higher, due to the ionization of the neutrals delivered. The charge collected in events closer to the wall is generally smaller. This can be due to the fact that ionization of neutrals produced upon impact is less effective closer to the wall than deeper in the SOL. Moreover, some of the impacts on the probes can be produced by dust from wall impact ejecta (a side effect already observed in dust impact ionization studies in vacuum environment [10]), which can be smaller in size and/or with lower velocity. It is worth to note that ejecta, produced by hypervelocity dust impact on the wall, and impinging on the probes, also explain the increase of the events rate closer to the wall. A particular feature of the events of very large amplitude (> 6 rms) is that they have exponential decay with the same characteristic time: the spread of the decay time for different amplitude thresholds (6, 8 and 10 rms) is within 10-30%. The typical decay time decrease closer to the wall from 70 μs (6 mm from the wall) to 40 μs (2 mm). These observations suggest that the decay time does not depend on the dust impact parameters and might be a function of the background plasma conditions (e.g. temperature and density). Measurements of plasma parameters close to the wall might be, therefore, based on the measurement of the decay time, provided proper modelling of the ion collection dynamics and suitable calibrations are performed.

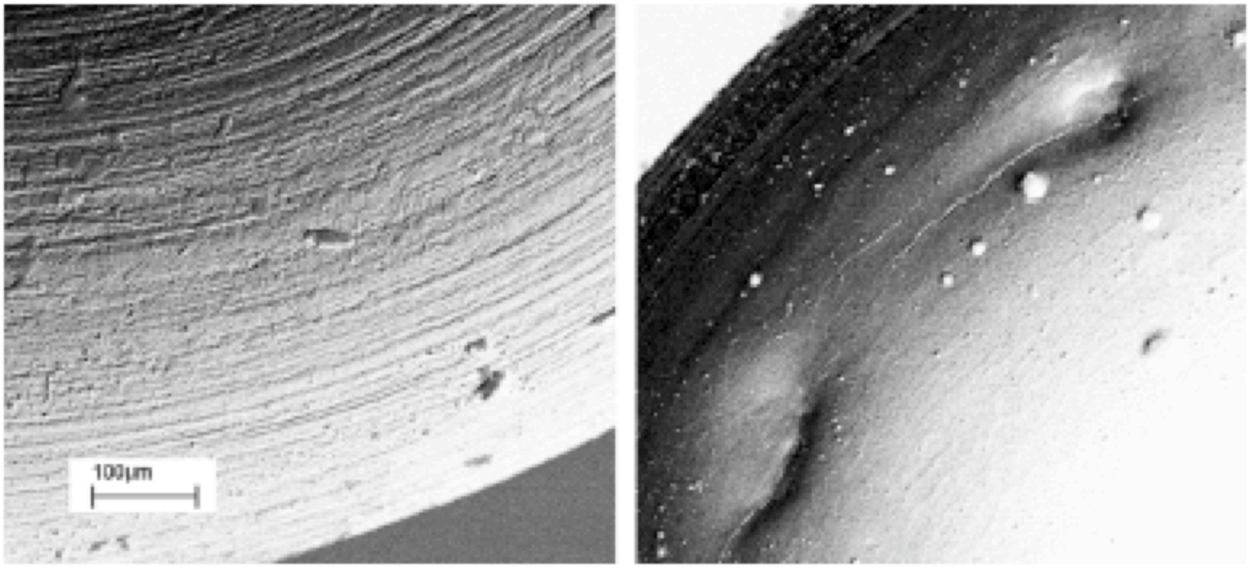

FIG. 2 - Electron microscope analysis of the surface of the unexposed probe (left) and probe used in the measurements (right).

Impact craters observed on the probe surface by SEM yielded direct support for the interpretation of the large amplitude current spikes detected by the probes in terms of dust impact ionization (see figures 2 and 3). The surface of the probe exposed to the plasma exhibits craters in the range from several to hundreds microns, while no craters where observed on the unexposed probe (see Fig. 2).

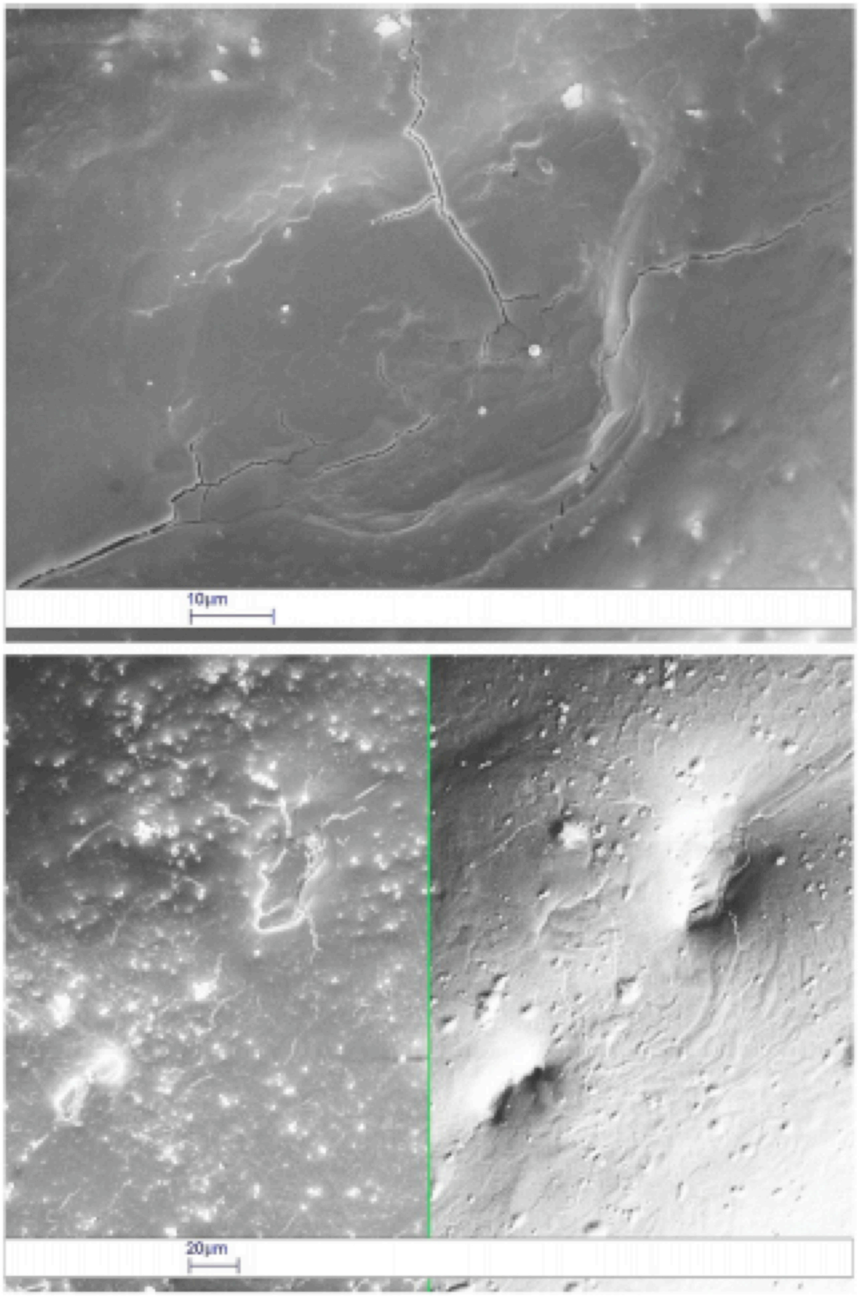

FIG. 3 - SEM images of the exposed surface of the probe. Indicated scale is 10 μm for the upper and 20 μm for the lower figure. Images at top and bottom left are taken by secondary electron detector; the bottom right is taken by EBS (electron back scattered) detector.

The surface of the exposed probe is smoothed by plasma exposure with spherical shaped particles of a micrometer size embedded in the surface. The majority of these particles have an 80% iron composition evaluated by energy dispersive x-ray (EDX) analysis. This is also in agreement with previous studies; 15% of the dust samples collected in TEXTOR-94 tokamak were ferromagnetic, containing a large number of iron rich spheres with a texture suggesting that they were exposed to the plasma [11].

The results of empirical formulas for the charge delivered upon iron dust impacts on molybdenum surface were compared to the charge collected by the probes. Empirical formulas were also used to evaluate the diameter of the craters produced upon impact of micron size iron particle on basalt targets [12]. For head-on collision of 1 μm radius iron particle impinging at a velocity of 20 km/s the estimated diameter of the crater is 100 μm. The range down to several μm can be easy covered with smaller angle of incidence and/or smaller velocities/sizes.

It is worth commenting the difference between the topography of a surface after impacts and that after events of unipolar arcs common for tokamaks [13]. The configuration of the craters found on the probe is very smooth, i.e. the rough rims from ejected molten metal typical for unipolar spots are missing. Plasma etching could have affected the craters, erasing such features. However, this seems not to be the case, because it still possible to see the roughness from the machining of the probe surface (see Fig. 2). The cracks observed (see Fig. 3) also suggest the occurrence of impact rather than arcs since the surface damage by the latter is mainly due to heating by arc current which cause melting of the material. Moreover, in tokamaks, the arc hops from one spot to another, causing scratch typically in several millimeters length [14]. Such scratches were never found on the probe surfaces used in the experiment.

For the statistics of the craters an optical microscope has been used, which allow detection only of craters larger than 10 μm. The average number density of the craters found is about 20 mm^{-2}, and the total number of the craters on the exposed surface of area $\sigma = 0.3$ cm^2 was estimated in the range 500-700. This is in agreement with the number of impact events estimated by the rate of the large amplitude current spikes (of the order of 100 Hz) and the total exposure time (about 10 s).

A rough estimate of the number density n_d of fast particles detected in the SOL of FTU during the experiments can be obtained fro the average rate $R = n_d\, \sigma\, v_d$ of the observed spikes. Near the wall, for impact velocities in the range 10-30 km/s, we found $n_d \approx 10^{-4} - 10^{-3}$ cm^{-3}.

Depending on the rate of the hypervelocity impacts, both wall erosion and plasma contamination by ejected material might represent potential hazards in continuous operation of fusion reactors [4]. Hence it is essential to monitor the fast dust population. A new method for in-situ dust collection has been recently proposed and is based on the use of "aerogel", a highly porous, very low density material [6]. Aerogel collectors can capture dust grains without destroying them, even in the high velocity range. Analysis of the tracks of captured particles allows to evaluate the dust velocity and the dust composition can be deduced upon particle extraction [15]. First choice candidate for tokamak application are silica (SiO_2) aerogels [6]. They are composed of clusters of 2 -5 nm solid silica spheres with up to 95 % empty space, an average pore size is 2-50 nm and mass density 0.1 g/cm^3. Studies of compatibility of pure silica aerogels with plasma conditions near the walls and tokamak vacuum requirements have been carried out [6]; (i) It has been demonstrated that sample out-gassed species are dominated by vapour of H_2O with traces of N_2 and CO, O_2 and CO_2 and they are easily pumped; (ii) Erosion of silica aerogel samples does not appear to present a serious problem for typical SOL conditions. The first experiments with silica aerogels exposed to SOL plasma have been performed recently in medium size HT-7 tokamak in Hefei, China (plasma current of 130 kA, magnetic field 1.8 T and line averaged plasma density 10^{19} m^{-3}) and reversed pinch EXTRAP (Stockholm, Sweden). Plasma exposure of samples was in the range of seconds; in both experiments the samples have been successfully extracted and preliminary surface analysis (x-ray tomography, SEM) revealed presence of dust traces.

On the FTU side, the mechanical design and construction of the sample holder have been finalized and the sample introduction system has been improved to allow the aerogel introduction in the coming campaigns. Such experiments at FTU are necessary to complement ongoing investigations at other metal machines, e.g. EXTRAP, and hence to allow a comparative study and shed light on the mechanism of acceleration of dust – still an open issue. Another diagnostics under development is an electro-optical probe for detection of dust impact ionization events by the ion saturation current spikes and the associated emission of light.

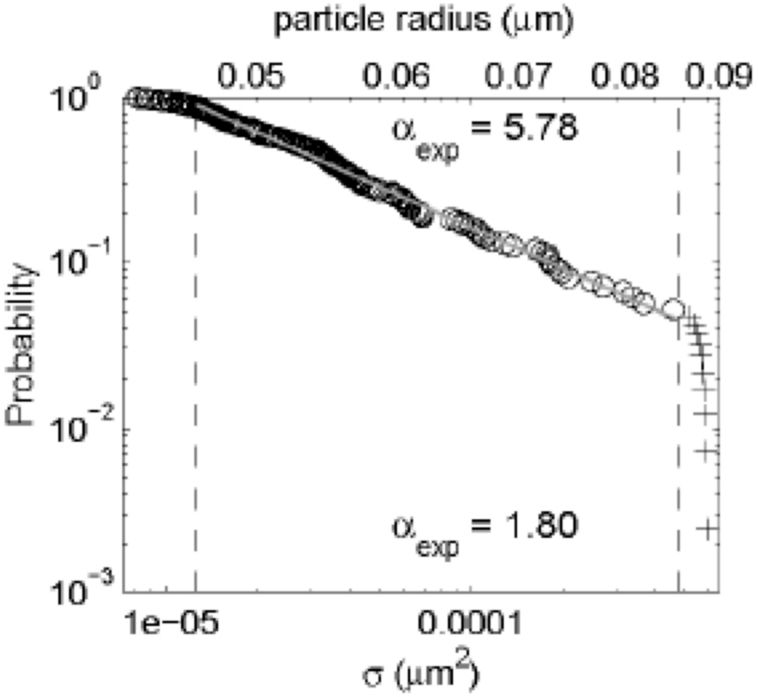

FIG. 4 - Experimental cumulative distribution function of particle cross-sections and radii using the Rayleigh approximation in the central spectrometer. Data to the right of the last dashed vertical line (+) are saturated.

Thomson scattering diagnostics have been used in tokamaks for estimating the dust size and density during normal plasma discharges as well as after disruptions. A characterization of the dust component present in the FTU vacuum chamber has also been attempted by laser light elastic scattering [5]. It was based on the detection channels at the laser wavelength (λ = 1064 nm) that are used for calibration of the Thomson scattering diagnostics. As there are no scattering channels aiming at the SOL on FTU, the measurements have been carried out only after disruptions. No evidence of scattering by dust was found indeed in the main plasma during normal operations. Particle size was estimated from the intensity of the scattered light, with

Rayleigh modelling of the laser-dust elastic cross section. This approximation seems reasonable for particles with size less than 0.1 μm (about 10% λ). However, the diagnostics becomes very insensitive to particles smaller than a few tens nanometers, as the Rayleigh scattering cross section is proportional to the particle radius to the sixth power. Moreover, in the calculation the refractive index value of molybdenum was assumed. Molybdenum is the component of the toroidal FTU limiter and normally is the most abundant impurity in the plasmas. With the above assumptions the average radius of the dust grains detected after disruptions was found of the order of 50 nm. The average dust density was found about 10^7 m^{-3}, calculated as the total number of scattering events, divided by the product of the scattering volume and the total number of the laser pulses considered. The size distribution of the particles seems to follow a power law $\sigma^{-1.8}$, where σ is the geometrical cross section of the grains (see Fig. 4). For larger particles the generalized Mie scattering theory should be used, taking into account spheroidal shape parameters and off-axis Gaussian-beam illumination [16]. Preliminary results of this analysis carried out on FTU data, suggests that simple Rayleigh scattering approximation underestimates the particle radii by a factor 2-5.

Moreover, nonlinear laser-dust interaction are expected to occur, as the energy density of the focused laser beam, delivered in 10 ns, is of the order of a few MJ/m^2, and might be enough to vaporize dust particles with size less than a few μm. Generation of plasma in the vapour cloud is also possible. Therefore, scattering and absorption by vapour and plasma cloud should be also taken into account in evaluating the particle size. A signature of the presence of a dense vapour/plasma cloud was indeed found in FTU, namely the occurrence of a broadband emission, possibly due to neutral and ionized gas emission lines, well correlated in time with the light scattered at the laser wavelength [17].

A more accurate analysis, following Ref. [18] and including the study of the broadband signal correlated with elastic scattering signal, is planned in FTU in order to provide useful information on the dust size and composition.

The combination of different in-situ dust diagnostics and experiments on other machines, which complement the parameter space can provide insight on the problem of dust dynamics essential for estimation of potential hazards for future reactors.

References

[1] CASTALDO, C., DE ANGELIS U., TSYTOVICH, V. N., "Screening and attraction of dust particles in plasmas", *Phys. Rev. Lett.* , **96** (2006), 075004

[2] DE ANGELIS, U., et al., "Fluctuations in dusty plasmas", *Plasma Phys. Contr. Fusion*, **48** (2006), B91

[3] CASTALDO, C., et al., "Diagnostic of fast dust particles in tokamak edge plasmas", *Nucl. Fusion*, **47** (2007), L5

[4] RATYNSKAIA, S., et al., "Hypervelocity dust impacts in FTU scrape-off layer", *Nucl. Fusion*, **48** (2008), 015006

[5] GIOVANNOZZI, E., et al., "Dust measurement with Thomson scattering in FTU" in "Burning Plasma Diagnostics International Conference", Varenna, Italy 24-28 September 2007, AIP Conf. Proc. Vol. 988 (2008) pg. 148

[6] RATYNSKAIA, S., et al., "In situ dust detection in fusion devices, Invited paper at 35th EPS, accepted to Plasma Phys.Contr. Fusion

[7] FRIICHTERNICHT, J. F., "Micrometeoroid simulation using nuclear accelerator techniques", *Nucl. Instr. Methods*, **28** (1964) 70

[8] ZWEBEN, S. J. et al., "Edge turbulence imaging in the Alcator C-Mod tokamak", Phys. Plasmas **9** (2002) 1981

[9] ANTAR, G. Y., et al, "Turbulence intermittency and burst properties in tokamak scrape-off layer", *Phys. Plasmas* **8** (2001) 1612

[10] WILLIS M.J., Burchell M.J., Cole M.J. and McDonnel J.A.M. 2004 *Planet. Space Sci.* **52** 711

[11] WINTER, J., *Plasma Phys. Control. Fusion* **40 (**1998) 1201

[12] BURCHELL, M. J., et al, " Hypervelocity impact studies using the 2 MV Van de Graaf accelerator and two-stage light gas gun of the University of Kent at Canterbury", *Meas. Sci. Technol.*, **10** (1999) 41

[13] JAKUBKA, K., and JÜTTNER, B., *J. Nucl. Mater.* **102 (**1981) 259

[14] FEDERICI, G., et al., "Plasma-material interactions in current tokamaks and their implications or next step fusion reactors", *Nucl. Fusion*, **41** (2001) 1967

[15] TSOU, P., "Silica aereogel captures cosmic dust intact", *Journal of Non-Crystalline Solids,* **186** (1995), 415

[16] HAN, Y., et al., "Generalized Lorenz-Mie Theory for a Spheroidal Particle with Off-Axis Gaussian-Beam Illumination", *Applied Optics* **42** (2003), 6621

[17] GIOVANNOZZI, E., et al., "*Dust in FTU with the Thomson scattering diagnostic",* Proceeding of 5th Intern. Conference on Physics of Dusty Plasmas, Azores, Portugal (2008).

[18] SMIRNOV, R. D., et al., "Laser-dust interaction and dust size distribution measurements on DIII-D", *Phys. Plasmas* **14** (2007), 112507