The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2052-64

Summer College on Plasma Physics

10 - 28 August 2009

Mobile Dust in Tokamak Sol Plasmas

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MOBILE DUST IN TOKAMAK SOL PLASMAS

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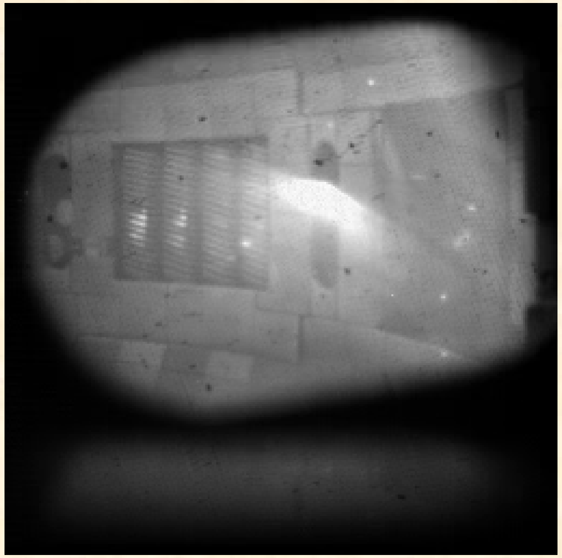
NOT MOVING

- Postdischarge methods are well established

- Analysis of deposits showed large spead in dust size from sub-μm to 100 μm

MOVING

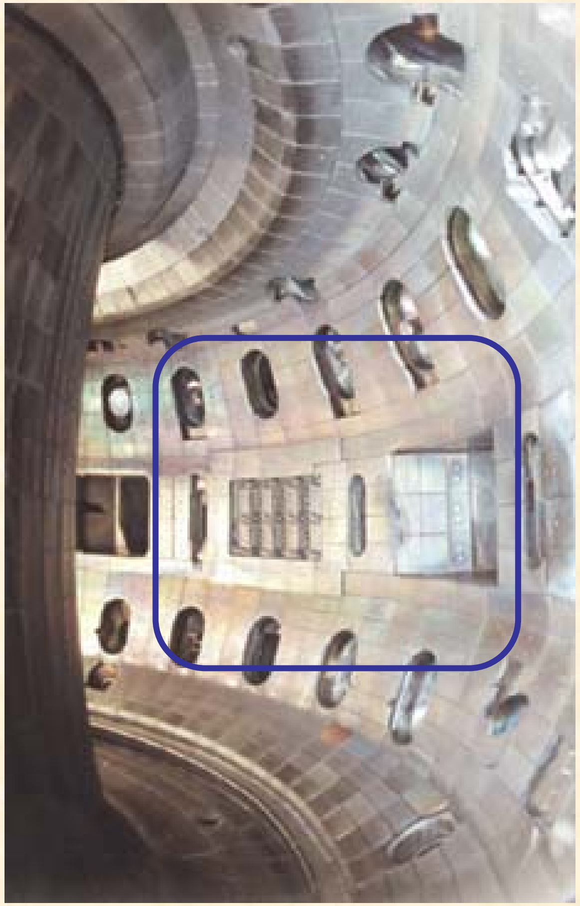


- Currently the main challenge is diagnostics of dust *during the discharge*

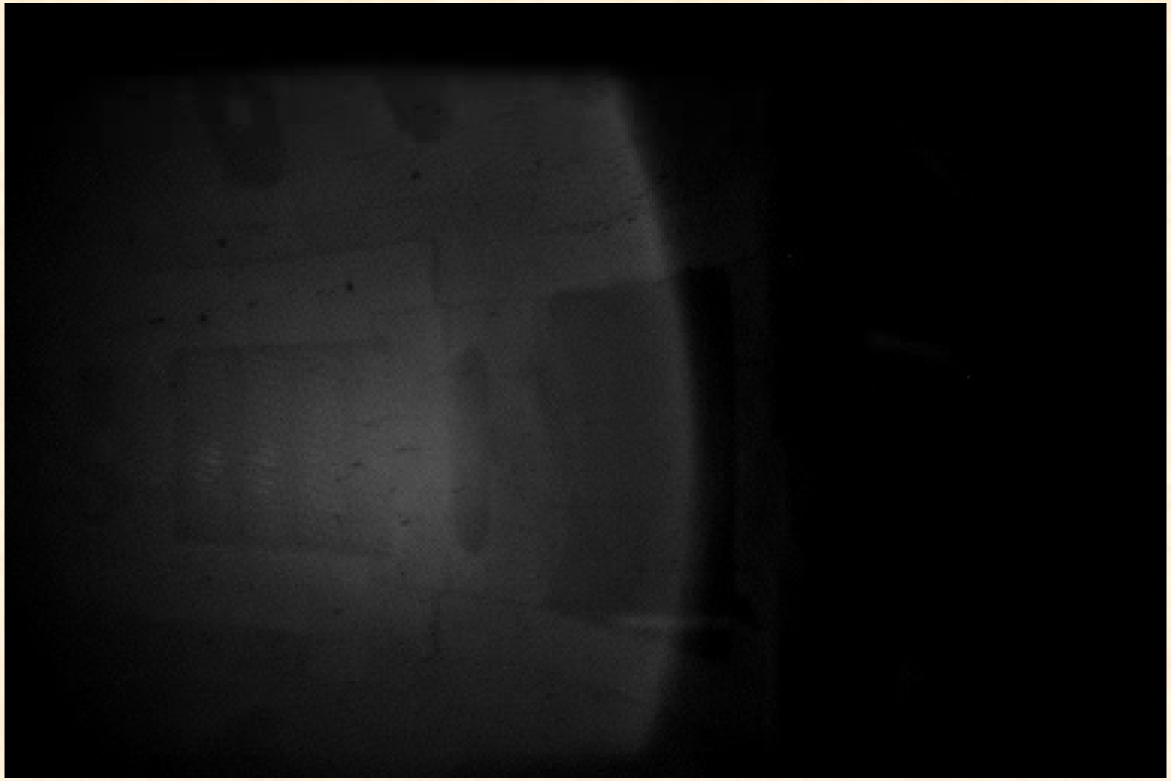
- Dust parameters of interest (apart from material), size, velocity and number density

DUST = safety and operational issues

DISRUPTIONS ARE SOURCES OF DUST



Shot number 131255,
upward vertical displacement event



Full light, 4000 f/s, total duration ~ 50 ms

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

DUST DYNAMICS

- **DUST CODES**

Plasma and neutral drags, electric and rocket forces

- Pigarov A. Yu. *et al* 2005 *Phys. Plasmas* **12** 122508
- Smirnov R. D. *et al*, 2007 *Plasma Phys. Control. Fusion* **49** 347
- Martin J. D., *et al* 2008 *Euro Phys. Lett.* **83** 65001

Other mechanisms :

- **Inelastic collisions with the wall for v>1 km/s**

- Krasheninnikov S. I.,et *al* 2008 *Plasma Phys. Control. Fusion* **50** 124054
- Smirnov R. *et al* 2009 *J. Nucl. Matter* **390-391** 84

- **Stochastic heating**

- Marmolino C. *et al* 2009 *Physics of Plasmas* **16** 033701

- **Role of arcs on metal dust**

- Castaldo C., invited paper 36th EPS, 2009 *Plasma Phys. Controlled Fusion*

DUE TO UNCERTAINTIES IN THE DUST PARAMETERS DIAGNOSTICS SHOULD COVER MAXIMUM PARAMETER RANGE

- **Visible imaging**

500 m/s for a bright dust grain of few μm

- **Impact ionization phenomenon**

Evidence of velocities of ~few km/s in FTU for a μm particle

- **Light scattering**

Detectable size (% of λ-few λ), laser λ~1 μm

- **Collective scattering**

Evolution of dust density during the discharge

- **Capture of dust (without destroying)**

Aerogels-light porous materials

- **Accumulated dust**

Electrostatic detector and microbalance technique

VISIBLE IMAGING

- **Single camera view – lower bound estimates**

Dust velocities projected on a plane perp. to line of view

- **Multiple cameras with intersecting views**

Unfold 3D trajectory. Set-up on NSTX

[A.L. Roquemore *et. al.*, J. Nucl. Mater. **363-365**, 222 (2007).**]**

- **Individual particle observed with velocities up to 500 m/s**

- **Estimates of size from thermal radiation**

can be masked by radiation from the ablation cloud

- **Problems with small (less than few μm) and fast dust**

small = high sensitivity, also fast=high contrast w.r.t. background

- **Calibration by injections of pre-characterized dust**

DIII-D results: 4 μm is smallest resolved by fast cameras

[J.H. Yu *et al.*, ” 2009 *J. Nucl. Matter.* **390-391**, 216**]**

LASER LIGHT SCATTERING

- **Use of existing Thomson scattering diagnostics**

detection channels at the laser λ are used for dust detection based on elastic scattering

- **Particle size can be estimated**

from intensity of scattered light-with assumptions on geometrical and optical properties of grain

- **Averaged dust number density can be calculated**

as total number of scattering events divided by product of scattering volume and total number of laser pulses

- **First measurements:**

JIPPT-IIU after disruption, radius 0.4-1 μm

[K. Narihara, et al. NF, **37**, 1177 (1997)]

DIII-D SOL during discharge, 6 10^3 m^{-3}, 80-90 nm

[W. P. West et al, PPCF, **48**, 1661 (2006)]

FTU after disruptions, 10^7 m^{-3}, 50 nm

[E. Giovannozzi *et al.*, AIP Conf. Proc. Vol. 988, pg. 148 (2007)]

MIE SCATTERING ; ABLATION CLOUDS

- **For larger particles Mie scattering theory should be used**

- **Laser power used is enough to vaporize dust < than few μm**

Scattering and absorption from ablation cloud (vapour+plasma)

- **Thermal evaporation + Mie theory for spherical particles**

DII-D results: averaged size twice larger than RLS estimates

Power law $r^{-\gamma}$ with $\gamma = 2.8$

[R. D. Smirnov *et al.*, PoP **14**, 112507 (2007).]

- **Similar analysis on FTU data suggests**

RLS underestimates size by factor 2-5

- **Uncertainties in refractive index**
- **Geometrical parameters**
- **Non-linear laser-dust interaction**
- **Lack of statistics for scattering events by micron size dust**

COLLECTIVE SCATTERING

- Coherent scattering from electrons in the Debye shielding cloud with λ_D

- For laser $\lambda \gg \lambda_D$ transitional scattering cross-section $\sigma_0 Z_d^2$

where σ_0 Thomson scattering cross-section and Z_d dust charge number

- For $n_d Z_d^2 \ll n_e$ transition scattering should not significantly modify scattering by plasma electrons without dust

V.Tsytovich *et al.* J. Plasma Phys., 42, 429 (1989).

R. Bingham *et al.*, Phys.Fluids B3, 811 (1991);
erratum Phys. Fluids, B4, 283 (1992).

DUST IMPACT IONIZATION-FOR RARE FAST DUST

- For most materials the hypervelocity regime (when the impact speed > the speed of the compression waves both in the target and projectile) has been reached when the impact speed exceeds 2-3 km/s
- The temperature can be sufficient to cause vaporization and ionization of the materials.

- Diagnostics based on the phenomenon:

(i) charge released (ii) craters on the target surface

- Laboratory studies of impacts [M. J. Burchell et al, Meas. Sci. Technol. 10, 41 (1999).]

-charge 10^{11}-10^{13} e upon impact of ~1 μm Fe particle on Mo surface with velocity of few km/s

-(with t=10-100 μs) ~10 mA current –feasible to measure in SOL

- Probe measurements in FTU near the wall, equatorial plane

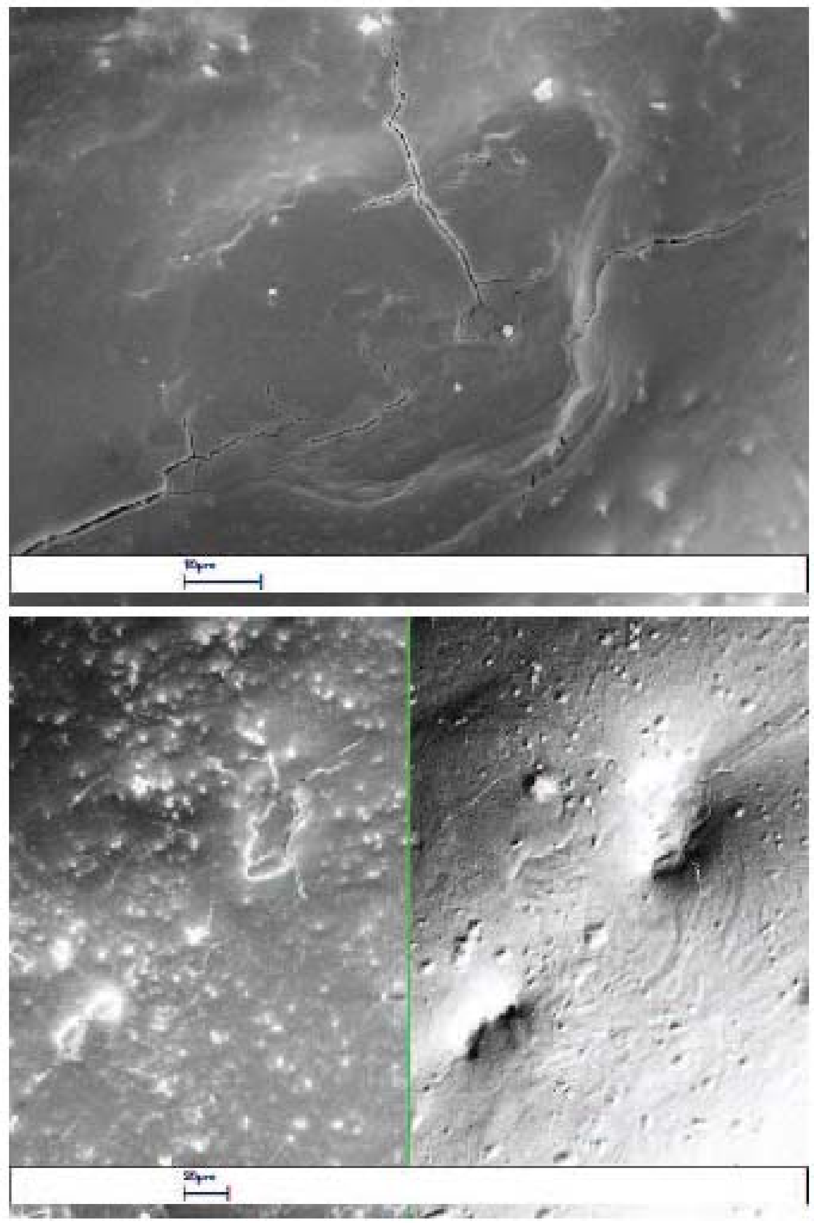
[C. Castaldo, S. Ratynskaia, V. Pericoli *et al.*, NF 47 L5-L9 (2007).]

[S. Ratynskaia, C. Castaldo, K. Rypdal *et. al.*, NF 48, 015006 (2008).]

DUST IMPACTS -CRATERS ON THE TARGET SURFACE

- Dimensions of the craters are function of the projectile parameters – empirical results available
- Craters smooth, no rough rims from ejected molten metal typical for the unipolar arcs
- Cracks observed - not typical for the arcs where surface damage is due to heating by the arc current
- Arc hops and leaves scratches on mm scale- none were found

[C. Castaldo *et al.*, NF 47 (2007)]
[S. Ratynskaia, *et. al.*, NF 48(2008)]

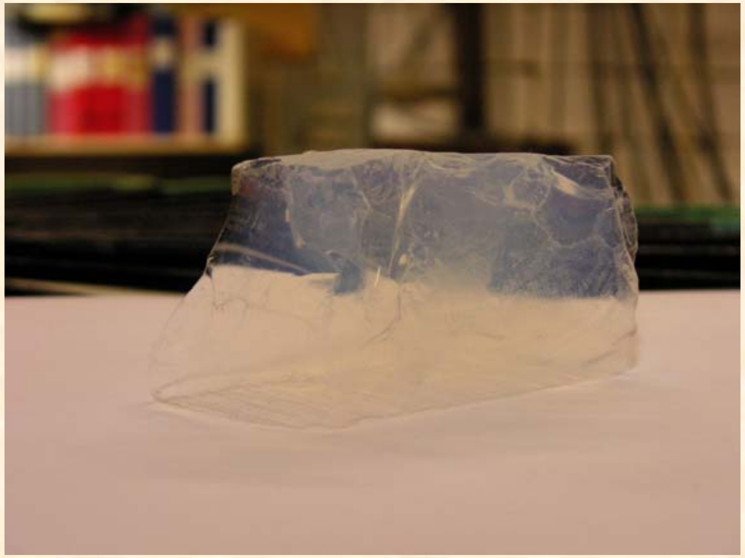


10μm

20μm

AEROGELS –DUST CAPTURE WITHOUT DESTRUCTION

- **Highly porous, very low density material**
- **Silica (SiO_2) aerogels 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 few tens kg/m^3.**
- **Made by high temperature and pressure-critical-point drying of a gel composed of colloidal silica structural units filled with solvents.**



http://stardust.jpl.nasa.gov/tech/aerogel.html

FIRST EXPOSURES IN TEXTOR

- The first *time-resolved* exposures in the TEXTOR scrape-off layer plasma showed that such targets are able to capture both slow and fast particles with sizes in the range from submicron to ~ 100 mm

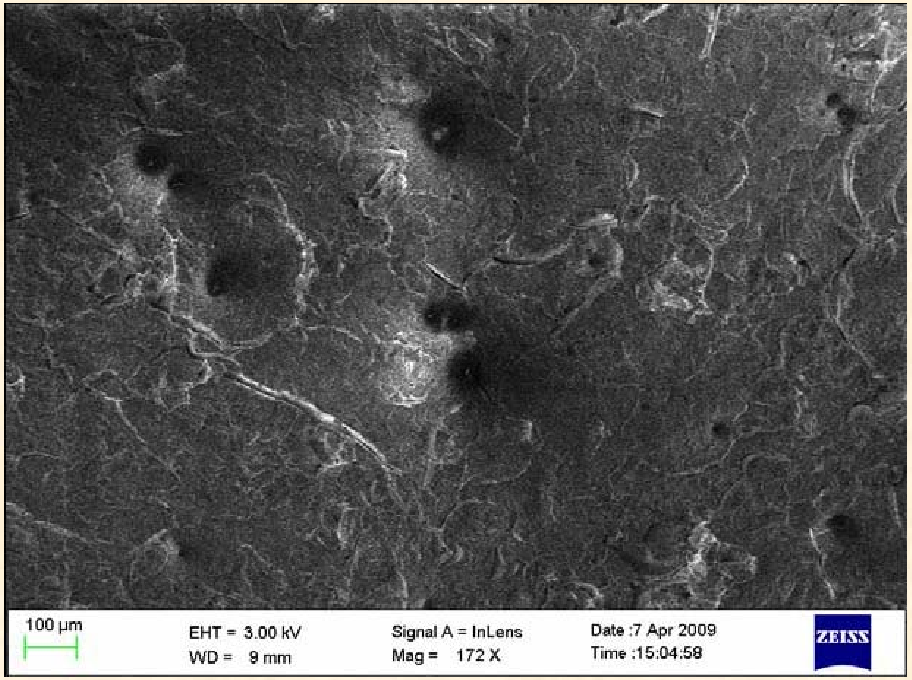
- The technique provides information on dust velocity and size distribution, dust flux estimates as well as a composition and texture of the captured dust can also be studied.

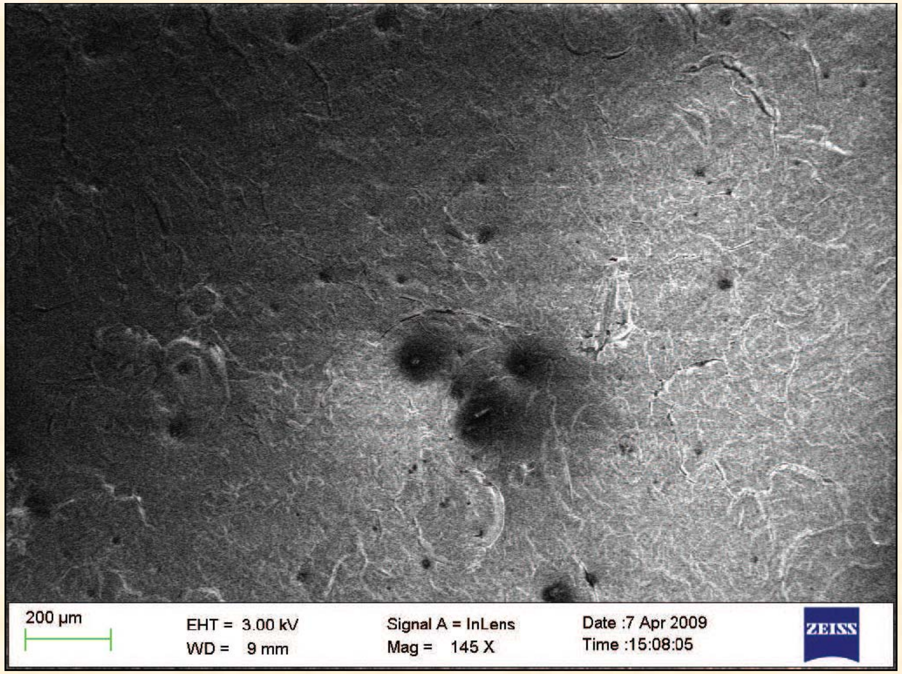
EXPERIMENTAL SET-UP

- Silica aerogel of density 60 kg m^{-3} , 10 × 9 × 35 mm
- Exposed in the outer midplane at minor radii 47.5 < r < 55 cm.
- Discharges limited by ALT-II toroidal limiter at r=46 cm and the SOL extends to r=55 cm.
- Exposures in SOL plasma during ohmic 350 kA shots with line-averaged density 2.5×10^{19} m^{-3}, with the probe leading edge at r = 50 cm.
- Samples exposed separately
  -to start up (0 < t < 1.3 s)
  -flat top (2 < t < 3 s)
  -ramp down (3.7 < t < 5.4 s).

SEM IMAGE OF AN EXPOSED SAMPLE

craters with particle residing at the bottom

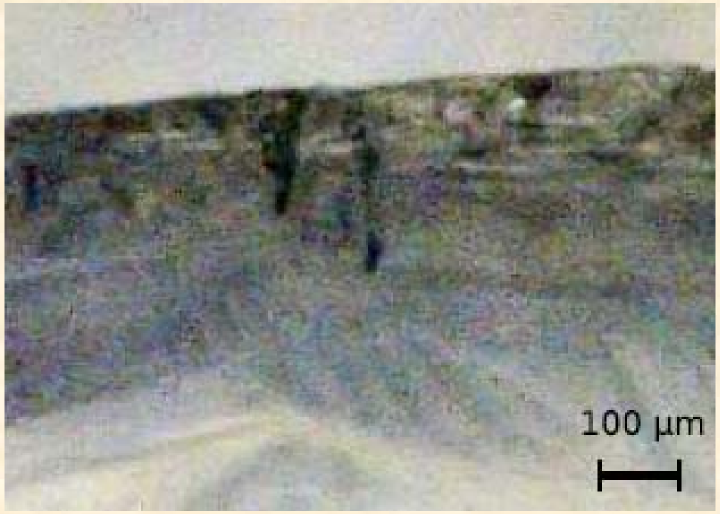




OPTICAL MICROGRATH

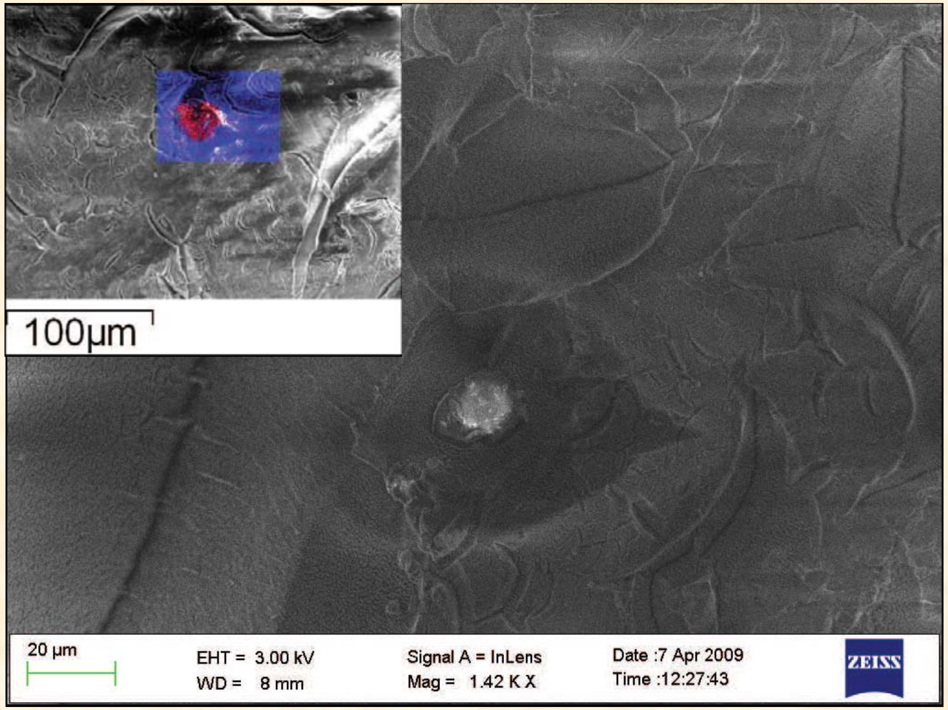
focusing an optical microscope at the surface from the side

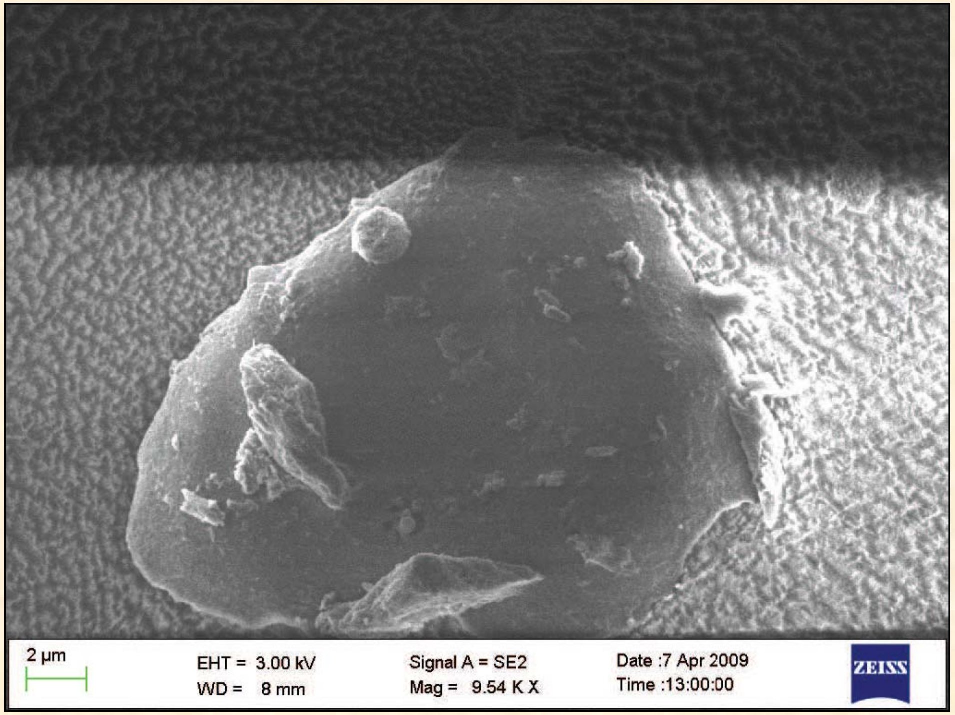
Impact tracks 60-500 microns long with particles residing at the bottom



SEM IMAGE

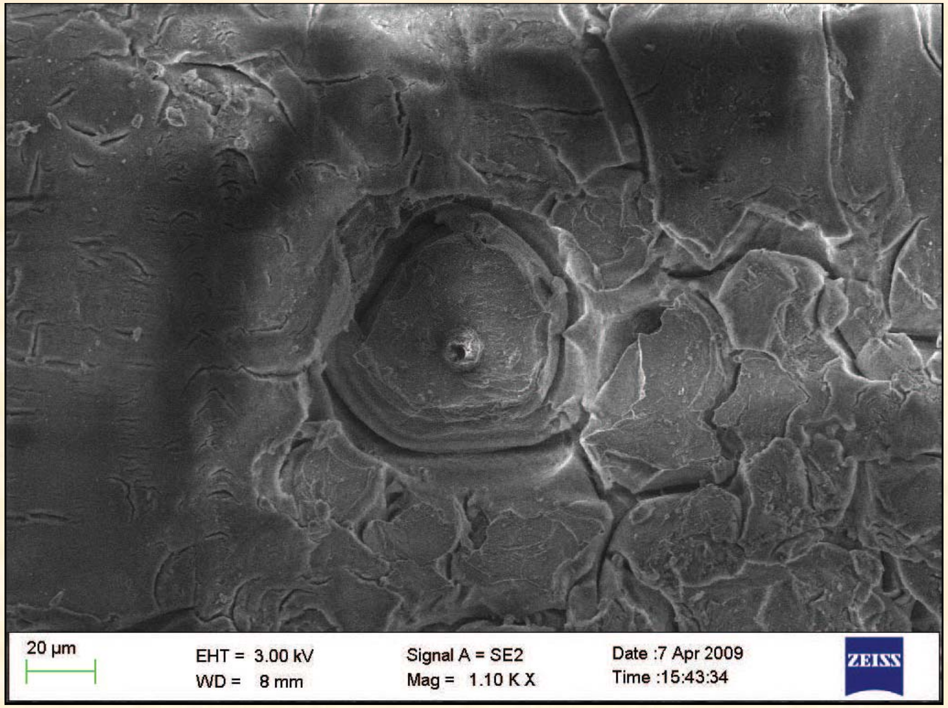
A shallow crater with a particle at the bottom (left) and zoom-in on the particle (right). The mapping of Si (blue) and C (red) (insert).

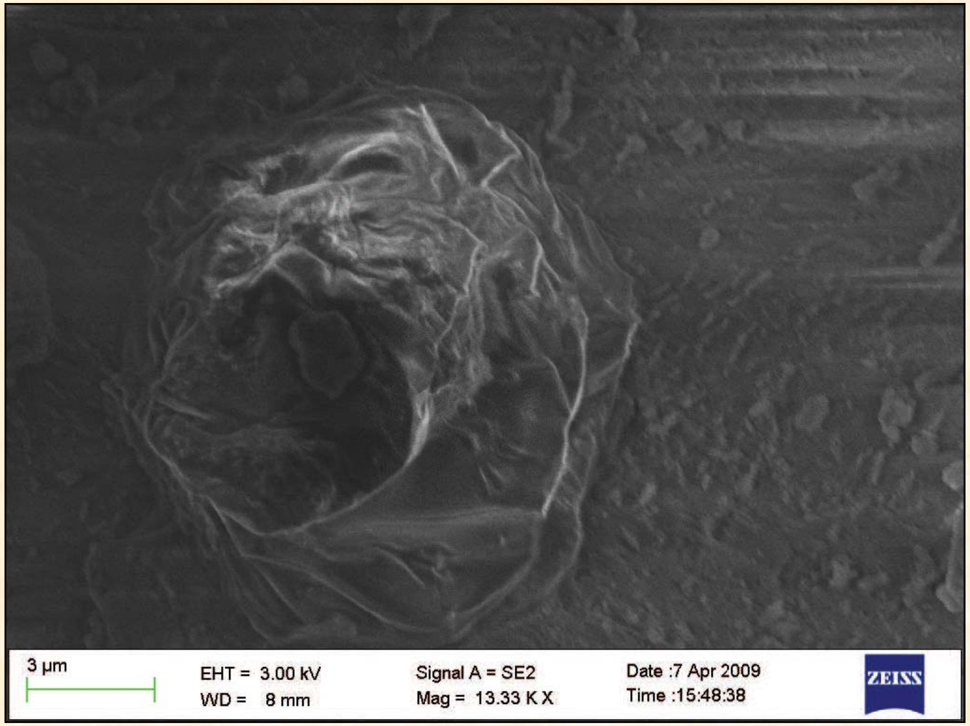




SEM IMAGE

The particle has penetrated, forming a narrow tunnel at the centre of the crater (left). Zoom-in on the tunnel (right), the intact particle is clear visible at the bottom.





RESULTS FROM SPACE RESEARCH

Laboratory

- Particles of known shape, size and composition are accelerated to desired velocities and shot into aerogel targets of selected densities

  (see e.g Kitazawa Y. *et al* 1999)
- =>

  Dependencies of penetration track properties (shape, length,volume) on the physical parameters of the projectile.

- The majority of such empirical results are available for comparatively large dust (100 μm) with impact velocities

  of several km/s and for space relevant particle materials

  (silicates and aluminium oxide)
- =>

  Need for calibration for fusion relavent dust materials , sizes and velocities

Modelling

- The physics of propagation of a shock wave of compressed target material.
- The shock wave stops expanding when its kinetic pressure is equal to the crushing pressure of aerogel.

- The latter is $P_c = ½ \rho v_c^2$, where v_c is the critical crushing velocity [Domınguez G. *et al* 2004, Trucano T. G., Gardy D. 1995].

- The crushing pressure, found experimentally

  $P_c(\rho)=6 (\rho / 14 \text{ mg cm}^{-3})^{2.04}$ kPa

  For ρ = 60 kg/m^3, the crushing pressure is Pc = 1.2×10^5 Pa and the corresponding critical velocity for crushing is v_c = 62 m/s [3].

APPLICATION for PRESENT DATA

Laboratory

- At the moment, the best approach is to scale the available dependencies to the parameters relevant for this study.
- Such estimates are not very accurate, but can yield at least some limits for impact velocities etc, until calibrations and/or models have been extended and improved.
- As an example, tracks with 10 μm diameter particles appear to have a volume of 10^{-13} m^3, hence extrapolating from Fig.13 of Burchell M. J. *et al* 2009 one can deduce a velocity of 2-3 km/s.

Modelling

- Correlation between the track length and the impact velocity (such as, e.g., Eq.(19) of Domınguez G. *et al* 2004) give velocities of few 100 m/s corresponding to track lengths of a few 100 μm.
- Since the cross sections of the observed tracks are usually significantly larger than the particles, that scaling provides lower limit estimates.
- For reconstruction of the original impact velocity the total energy balance, which includes energy needed to crush the aerogel along the track as well as energy spent on heating, melting and other processes, must be addressed.

CONCLUSIONS

- Experimental input on fast dust in tokamaks is very timely as well as necessary to shed a light on dust acceleration mechanisms.

- The first time-resolved dust capture by aerogel targets in a tokamak SOL plasma have been carried out.

- Most of the dust of ohmic discharges was collected during the flat-top phase, a particle flux density of 20-50 particles cm^{-2} s^{-1}, for particles that were sufficiently big to be visible optically (> 10 μm) and sufficiently fast to stick to the surface.

- Surface analysis of exposed samples allows conclusions about size distribution (from submicron to 100 μm) and dust texture and composition as well as lower limits for dust velocities.

- For more precise estimates, in particular of the upper velocity limits, laboratory calibrations of the impacts are desirable.

REFERENCES

- **Ratynskaia S., Castaldo C., Rudakov D. *et al* 2008 *Plasma Phys. Contr. Fusion* 50 124046**

- **Ratynskaia S., Bergsåker H., Emmoth B., Litnovsky, Kreter A. , Philipps V. , *Nuclear Fusion*, submitted, 2009**

- **Kitazawa Y. *et al* 1999 *J. Geophys. Research* 104 22,035**

- **Burchell M. J. *et al* 2009 *Planetary and Space Science* 57 58**

- **Domınguez G. *et al* 2004 *Icarus* 172 613**

- **Trucano T. G., Gardy D. 1995 *Int. J. Impact Eng* 17 861**