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Acceleration of dust particles in tokamak edge plasmas.

U. de Angelis
Universita' di Napoli
Dip. di Scienze Fisiche
Italy

Acceleration of dust particles in tokamak edge plasmas

U. de Angelis
Department of Physical Sciences, University of Naples, Italy

C. Marmolino
Department STAT, University of Molise, Italy

Hypervelocity Particles in Fusion Devices

- Numerical codes for micron-size particles:
  Visible imaging

$$v \leq 200 \quad m/s$$

- Rudakov D. 2007 *1st Workshop on Dust in Fusion Plasmas* (http://cpunfi.fusion.ru/eps-dust-media2007/Rudakov.....S1-3)

$$\text{DIII-D size} \quad \geq 10\mu m, \quad v \geq 0.5 km/s$$

- Castaldo C *et al* 2007 *Nuclear Fusion*, **47** L5-L9
  Ratynskaia S *et al* 2008 *Nuclear Fusion*, **48** 015006

FTU: few km/s, micron-size particles

$\rightarrow$

IMPACT IONIZATION

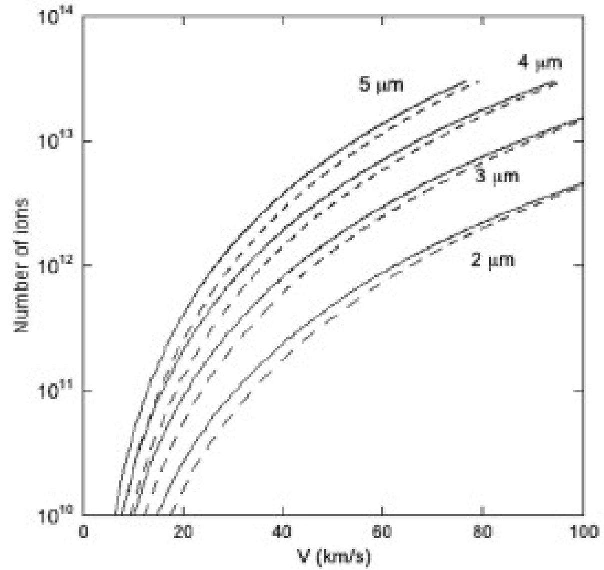
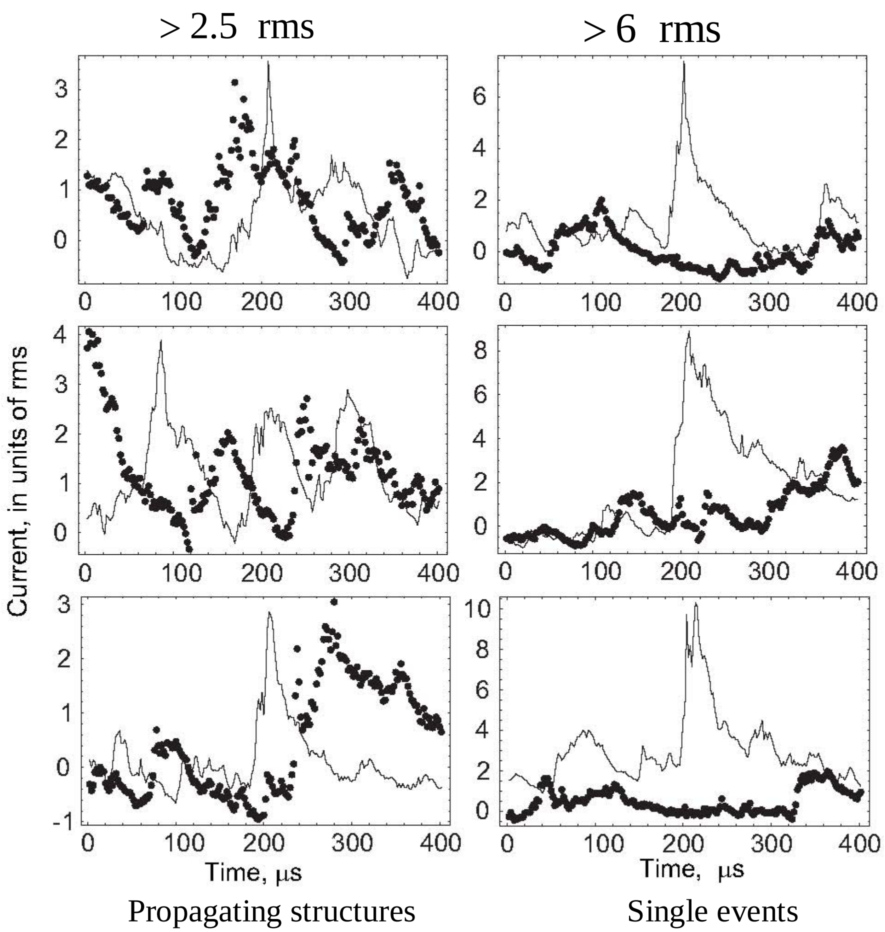
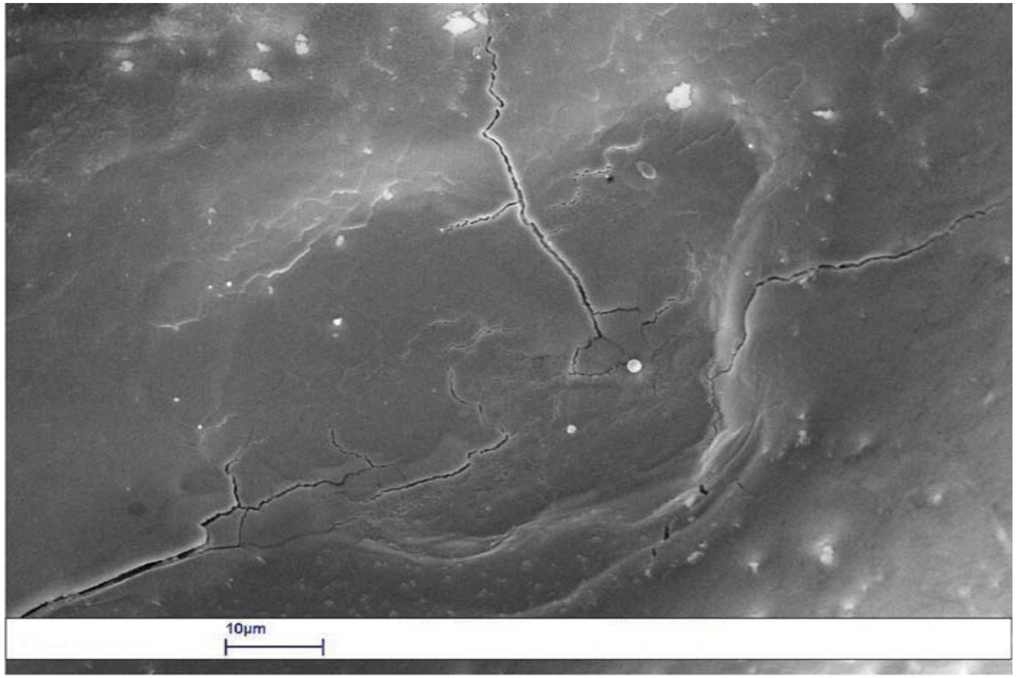
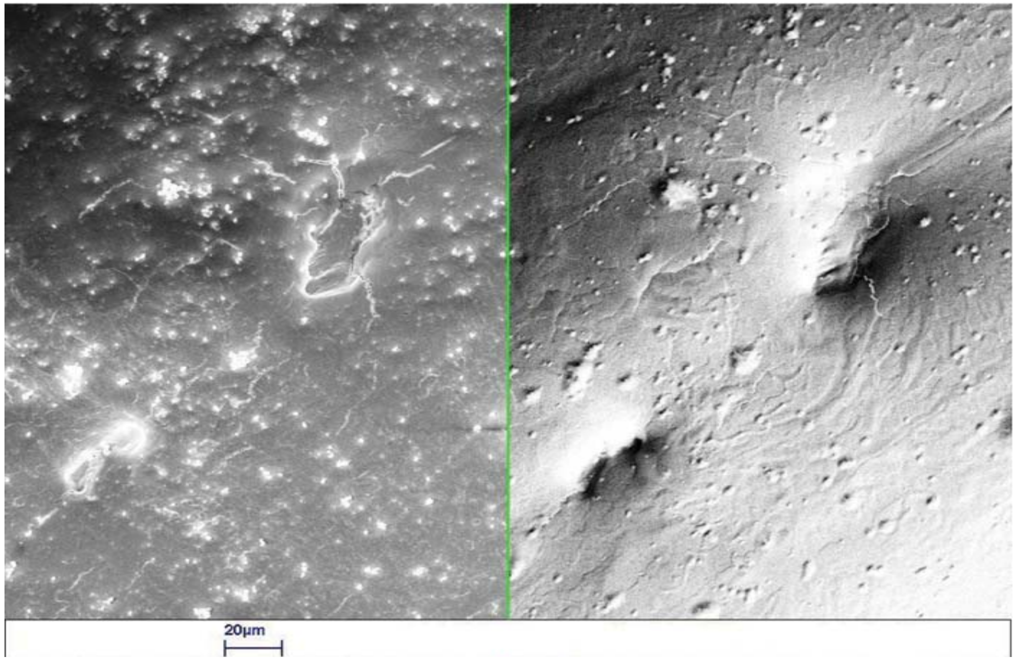


Figure 1. Results of the empirical expressions of [2]: number of ions produced upon impact of an iron projectile on a molybdenum surface target as a function of the projectile velocity and radius. The dashed line corresponds to the fast and the full line to the total ionization. See text for definitions.



- Two equatorial probes (separation 0.6 cm)
- Lack of correlation, expecially for largest fluctuations
- Very rare extreme events
- Rate increases towards walls


10µm


20µm

Mechanisms for the acceleration of dust particles in plasmas

in the conditions of the scrape-off-layer (SOL) in tokamaks

- Ion Drag
- Resonant scattering
- Stochastic heating

Ion drag (dominant force)

Ion drag force on a dust particle:

$$\vec{F}_{dr} = \nu_{di} m_i \left(\vec{u}_i - \vec{v}_d \right)$$

For constant ion drift, the velocity of a dust particle is:

$$v_d(t) = u_i \left(1 - e^{-\frac{m_i}{m_d}\nu_{di} t} \right);$$

In tokamaks the ion flow velocities are typically of the order of tens of km/s for toroidal plasma flow near the last closed magnetic surface (LCMS).

The time to reach a velocity:

$$v_d \simeq 0.5 u_i \qquad \text{is}$$

$$t_o \simeq 0.7 \frac{m_d}{m_i} \frac{1}{\nu_{di}}$$

For FTU SOL conditions:

$$T_i \simeq T_e = 30\ eV,\quad m_i = 3.3\cdot 10^{-24}\ \text{g},\quad n_i = 5\cdot 10^{12}\ cm^{-3}$$

Find (a_μ grain radius in microns):

$$\nu_{di} \simeq 2\cdot 10^{12} a_\mu^2 z^2\ \left(s^{-1}\right) \rightarrow t_0 \simeq 4\cdot 10^{-1}\frac{a_\mu \rho_d}{z^2} \simeq 0.7\ \text{s}$$

$$\text{For } a_\mu \simeq 1,\quad \rho_d \simeq 7\ \text{g}/\text{cm}^3,\quad z \simeq 2$$

When the ion drag is the dominant force on dust particles, these can reach velocities of the order of the ion flow velocities in times of the same order than typical discharge times.

Too long! (ablation: 1 ms)

Resonant Scattering

Resonance with plasma modes can lead to a large enhancement of the collision frequency:

U de Angelis, C Marmolino and V N Tsytovich *Phys. Rev. Letters*, **95**, 095003, 2005

$$\nu_{di}^{R} = \frac{16\pi\sqrt{2}e^{2}n_{d}v_{T_i}}{3T_i^{2}v_{T_d}}\int_{0}^{\infty} ye^{-y^{2}}\Lambda^{R}(y)dy$$

$$\Lambda^{R}(y) = \int_{0}^{k_{\max}(y)} \frac{\left|q_{k,\omega_M}^{eff}\right|^{2} e^{-\frac{v_\phi^2(k)}{2v_{T_d}^2}}}{\left|\varepsilon_{k,\omega_M}^{''}\right| \left|\frac{\partial\varepsilon_{k,\omega}^{'}}{\partial\omega}\right|_{\omega=\omega_M}} \frac{dk}{k^{2}}$$

$q_{k,\omega}^{eff}$: effective dust charge in interactions

$v_\phi(k) = \dfrac{\omega_M(k)}{k}$: wave phase velocity

Stochastic Heating

Dust charge fluctuations $\rightarrow$ non conservation of energy in dust-dust interaction

$$\varepsilon = \frac{1}{2} m_d \int v^2 \Phi^d (v) d^3 v; \quad \frac{d\varepsilon}{dt} = \nu\varepsilon$$

de Angelis *et al.*, *Physics of Plasmas*, **12**, 052301, 2005
Ivlev *et al.*, *Physics of Plasmas*, **12**, 092104, 2005

From both theories:

$$\nu \simeq \frac{1}{Z_d} \frac{\omega_{p_d}^2}{\nu_{ch}}; \quad \text{where}$$

ω_{p_d} is the dust plasma frequency

$\nu_{ch} \simeq \omega_{p_i} \dfrac{a}{\lambda_{D_i}}$ is the charging frequency

The dust particle mean velocities grow as:

$$V^2 = V_o^2 e^{\nu t}$$

Corresponding to an acceleration time:

$$t = \frac{2}{\nu} \ln \frac{V}{V_o}$$

The time to reach velocities of the order of 1 km/s, for a 1 μm iron particles is:

$$t(1) \simeq \frac{10^5}{n_d} ms$$

Requires $n_d > 10^5 cm^{-3}$!!

Two Step Model

Marmolino C, de Angelis U, Ivlev A & Morfill G E, *Stochastic Acceleration of Dust Particles in Tokamak Edge Plasmas*, 2008 these Proceedings

Nanoparticles are stochastically heated and transfer energy to microparticles via collisions:

For the case of dissipation on ions with energy Ti

$$\frac{d\varepsilon}{dt} = \nu\varepsilon - 2\gamma_n\left(\varepsilon - \frac{3}{2}T_i\right)$$

$$\frac{dE}{dt} = \Gamma\varepsilon^{1/2}\left(\varepsilon - E\right) - 2\gamma_\mu\left(E - \frac{3}{2}T_i\right)$$

Geometrical cross-section

$$\Gamma = n_d \frac{\sqrt{m}}{M}\pi A^2$$

Condition for growth

$$\nu_{eff} = \nu - 2\gamma_n > 0$$

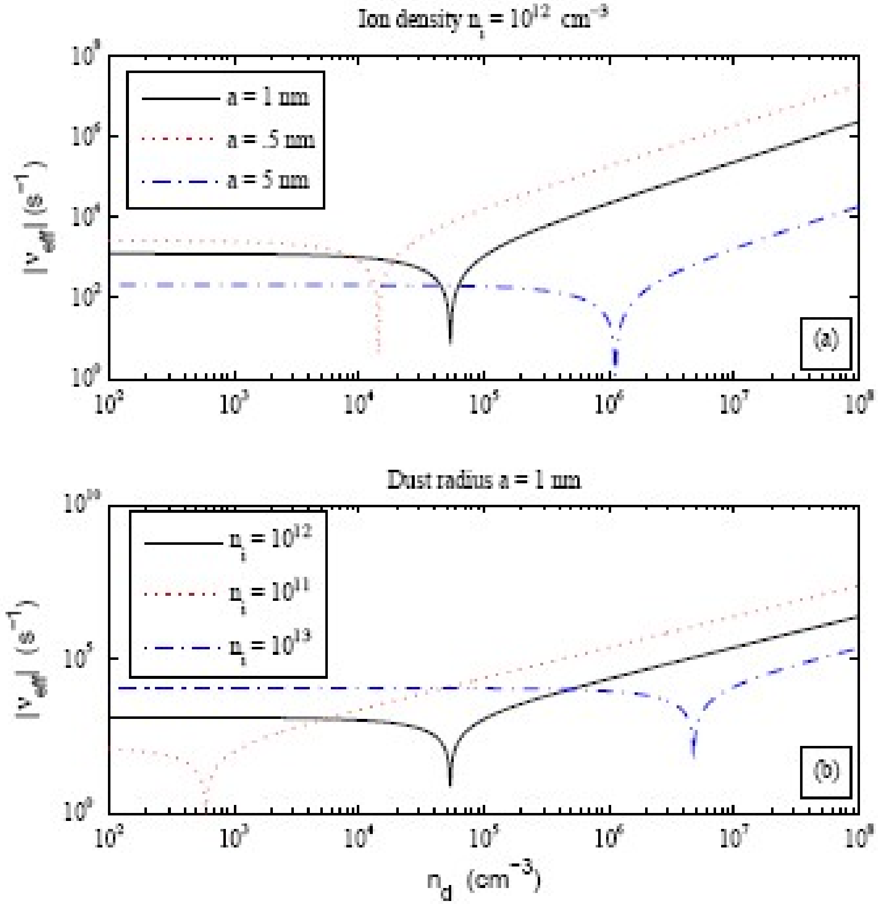


FIGURE 1. The absolute value of ν_{eff} versus the density of the nanoparticles for different values of their radius and a fixed ion density (a), and for different values of the ion density and a fixed grain radius (b). Notice that the plot is a log-log plot and ν_{eff} changes sign in the minimum, being positive to the right of the minimum.

Energy growth (FTU-SOL conditions)

a) $\nu_{eff} > 0$

$$\frac{\varepsilon(t)}{\varepsilon_o} = e^{\nu_{eff} t} + \frac{3\gamma_n T_i}{\nu_{eff}\varepsilon_o}\left(e^{\nu_{eff} t} - 1\right)$$

b) $\nu_{eff} < 0$

$$\frac{\varepsilon(t \to \infty)}{\varepsilon_o} = \frac{3\gamma_n T_i}{\left|\nu_{eff}\right|\varepsilon_o}$$

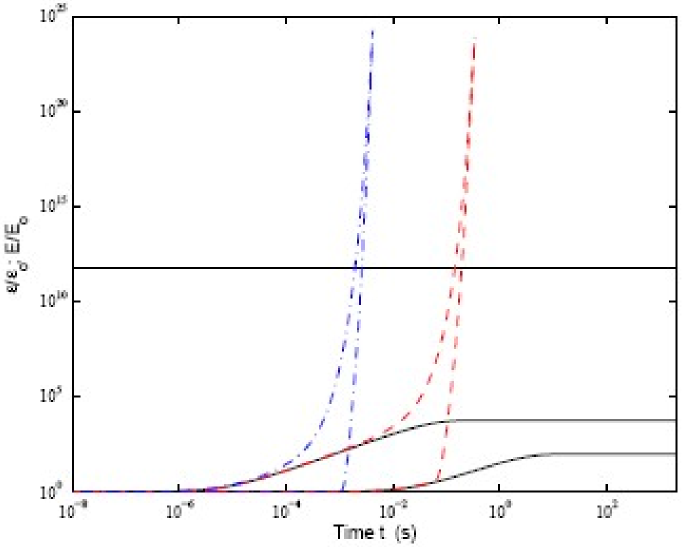


FIGURE 2. The normalized energy of the nano (ε) and micronsize (E) particles versus time in seconds, for different values of the density of the nanoparticles. For each pair, the curve for ε is the one with earlier growth. Full line $n_d = 5.3 * 10^4$ cm^{-3} (below the instability threshold, corresponding to $n_d = 5.3905 * 10^4$ cm^{-3}); dashed line $n_d = 6. * 10^4$ cm^{-3}; dot-dashed $n_d = 6. * 10^5$ cm^{-3}.