Lecture no.12

Basic Concepts about Nonideal Dusty Plasma

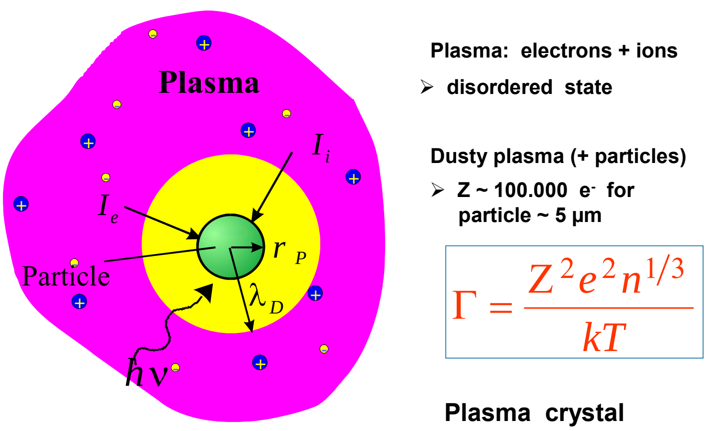
Introduction

Dusty plasma is the system consisting of the plasma's particles as well as of macropaticles of condensed matter. Other terms used for such systems are “complex plasmas”, “colloidal plasmas”, and “plasmas with a condensed disperse phase”. Such system is strongly coupled and forms liquid–like and crystal–like structures. Dusty plasma occurs in the nature and in many laboratory and technological devices.

Charging of dust particles in plasmas

It should be noted that dust particles immersed in a plasma acquire an electric charge and can be considered as additional charged component (see, Fig.1). Therefore the properties of dusty plasmas are much more diverse in comparison with the ordinary multicomponent plasmas consisting of electrons and different types of ions.The dust particles can be considered as recombination centers for plasma electrons and ions and as sources of electrons (thermo-, photo-, and secondary electron emission).It means that the dust component can significantly influence the plasma ionization balance. It should be also added that the dust particle charge is not fixed, but is determined by the surrounding plasma parameters, and can fluctuate even for constant plasma parameters.

Figure 1. The schematic representation of dusty plasma.



At the present time we can mention the following important directions in the of dusty plasma properties:

- formation of ordered structures, including crystallization and phase transitions in the dust subsystem;
- elementary processes in dusty plasmas: charging of dust for different plasma and particle parameters;
- interactions between the particles, external forces acting on the particles;
- linear and nonlinear waves in dusty plasmas (solitons, shock waves, Mach cones), their dynamics, damping, and instability.

There are four mechanisms for charging of dusty particles in plasma (see, Figure 2):

1) Capturing of electrons. In this case we have the following plasma parameters: $P = 0,1 \div 2\, torr$ is the pressure; $T_e = (1 \div 8)10^4 K$ is the temperature of electrons; $T_i = 300K$ is the temperature of ions; $n_e = 10^8 \div 10^{10} cm^{-3}$ is the electron density number; $Z = (10^4 \div 10^5)e$ is the charge of dusty particles ; $\Gamma = 10^4 \div 10^6$ is the coupling parameter.
2) Thermal-electron emission. The plasma parameters for this case as follows: $n_e \sim n_i = 10^9 \div 10^{12} cm^{-3}$ is the density number of electrons and ions; $n_d = 10^4 \div 10^7 cm^{-3}$ is the density number of dusty particles; $Z = (10^2 \div 10^3)e$ is the charge of dusty particles; $\Gamma \le 120$.
3) Photo-electron emission. By this mechanism the following plasma parameters can be realized: $P = 0,01 \div 40\, torr$ is the pressure; $T_i \approx T_n = (300 \div 400)K$ is the temperature of ions; $n_d = 10^2 \div 10^3 cm^{-3}$ is the density number of dusty particles; $Z = (10^3 \div 10^4)e$ is the charge of dusty particles; $\Gamma \sim 10^4$.
4) Radioactive generated plasma. In this case we can reach the following plasma parameters: the fission energy is $E_f = (5 \div 100)MeV$; the energy of beta decay is $E_\beta = 100keV$; $Z = (10^2 \div 10^3)e$ is the charge of dusty particles; $\Gamma \sim 100$.

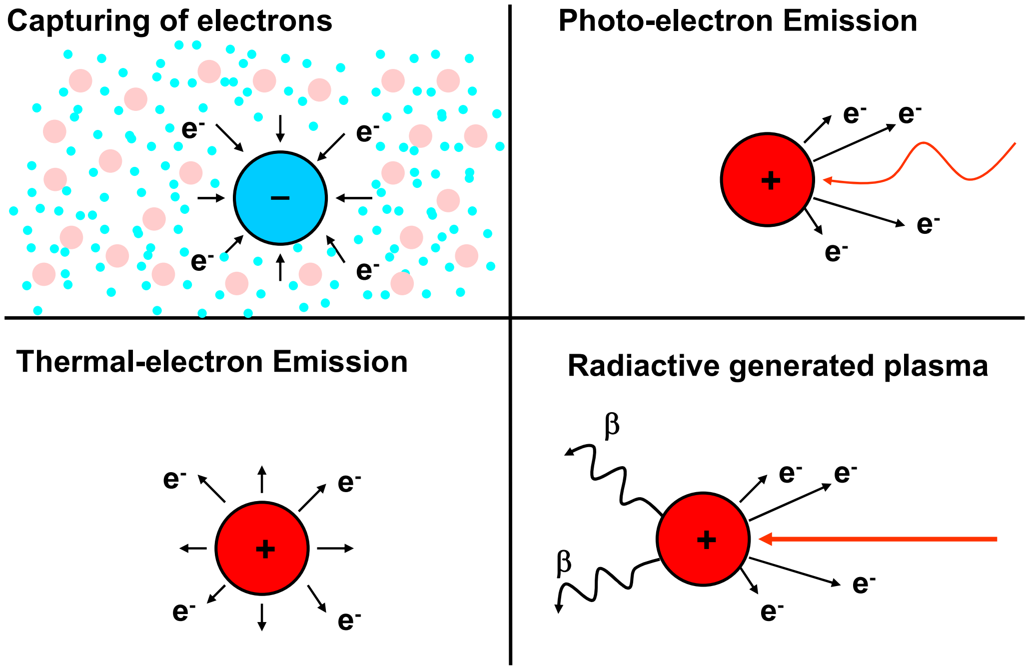


Figure 2. The different charging mechanisms of dusty particles in plasma.

The photo of dusty particles obtained by electronic micrography is presented in the Figure 3. As one can see it looks as “cauliflower”.

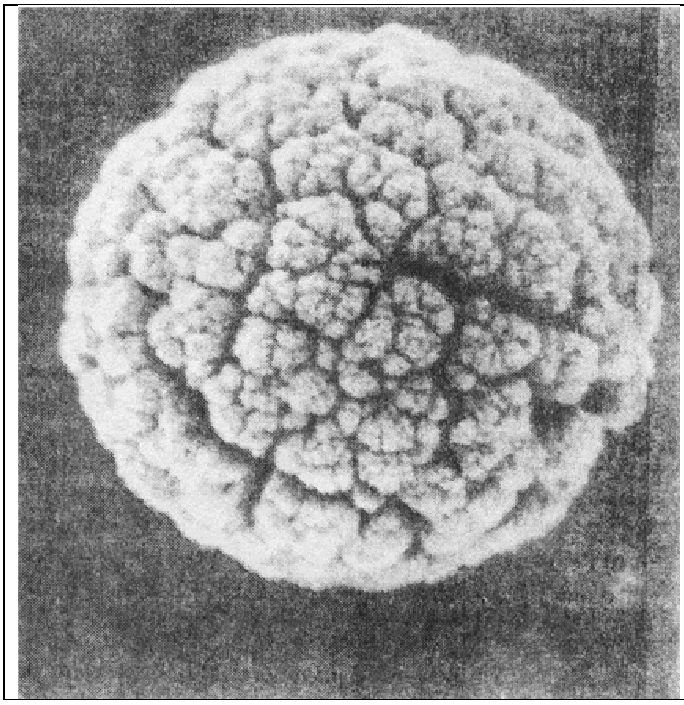


Figure 3.

Photo of dusty particle was formed in RF discharge (15 MHz, 1 Torr) and obtained by electronic micrography (A.Garscadden e.a, 1994)

(“Cauliflower”)

Some peculiarities of dusty plasma. OML theory

Let us represent some peculiarities about specific processes in dusty plasma.

- If the dusty particle charge in the unit volume is more than the charge of free electrons, i.e. $n_d Z_d / n_e \geq 1$, then the collective influence of particle-grain interaction on plasma processes is significant.
- The charge of dusty particles is the variable quantity and depends on parameters of surrounding medium.
- The screening of electrical field of dusty particles is realized at the following Debye radius:

$$\frac{1}{D^2} = \frac{1}{d_e^2} + \frac{1}{d_i^2} , \qquad (1)$$

where d_e, d_i are the Debye radii of electrons and ions, respectively. Since in many experiments the condition $d_i \ll d_e$ is realized, then screening process is defined by radius of ions and the linear size of dusty particles satisfies the following condition $a \ll D$.

- In order to consider the dust component as the additional component of plasma it is necessary to realize the following condition for particles in Debye's sphere of dusty particles.

$$N_d = \frac{4\pi}{3} n_d D^3 \gg 1 \qquad (2)$$

In this case the resulting Debye's radius is defined as follows:

$$\frac{1}{r_D^2} = \frac{1}{d_e^2} + \frac{1}{d_i^2} + \frac{1}{D^2} . \qquad (3)$$

It should be noted that if the distance between dusty particles is more than r_D then the interaction between macroparticles is non-coulomb.

- Due to the high rate of dissipation, the plasma particle's fluxes recombined on dusty particles must be supported by external sources. Since the dusty plasma is the open system the probability of ordered structures formation in such system is high.

Orbit motion limited (OML) approximation. In order to describe of particle charging in gas discharge plasmas some methods are used. One of the most frequently used approaches is the orbit motion limited (OML) theory. According to this theory the cross–sections for electron and ion collection by the dust particle are determined only from the laws of conservation of energy and angular momentum. The conditions of applicability of the OML theory are formulated in the following form:

$$a \ll r_D \ll l_{i(e)}, \tag{4}$$

where $l_{i(e)}$ is the mean free path of the ions (or electrons). It is also assumed that the dust particle is isolated and other dust particles do not affect the motion of electrons and ions in its vicinity.

In the OML theory it is assumed that the electrons and the ions are collected if their trajectories cross or graze the particle surface. In this case the corresponding velocity–dependent cross–sections are given by the following expressions:

$$\sigma_e(\upsilon) = \begin{cases} \pi a^2 \left(1 + \dfrac{2e\varphi_s}{m_e \upsilon^2}\right), & \dfrac{2e\varphi_s}{m_e \upsilon^2} > -1 \\ 0, & \dfrac{2e\varphi_s}{m_e \upsilon^2} < -1, \end{cases}$$
$$\sigma_i(\upsilon) = \pi a^2 \left(1 - \dfrac{2e\varphi_s}{m_i \upsilon^2}\right) \tag{5}$$

where m_e and m_i are the mass of electrons and ions, respectively; υ is the velocity of the electrons and ions relative to the dust particle; the surface potential φ_s of the dust particle is negative and the ions are singly charged.

Knowing the corresponding cross–sections and velocity distribution functions $f_{e(i)}(\upsilon)$ the electron and ion fluxes to the particle surface can be determined by the following integration:

$$I_{e(i)} = n_{e(i)} \int \upsilon \sigma_{e(i)}(\upsilon) f_{e(i)}(\upsilon) d^3\upsilon \quad . \tag{6}$$

If we use the Maxwellian velocity distribution of plasma particles:

$$f_{e(i)} = \left(2\pi\upsilon_{T_{e(i)}}^2\right)^{-3/2} \exp\left(-\frac{\upsilon^2}{2\upsilon_{T_{e(i)}}^2}\right) \quad , \tag{7}$$

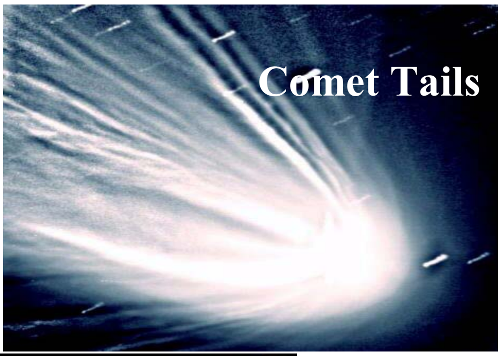
where $\upsilon_{T_{e(i)}} = \sqrt{k_B T_{e(i)} / m_{e(i)}}$ is the electron (ion) thermal velocity. Integration in equation (6) with using (5) and (7) gives the following expressions for electron and ion fluxes:

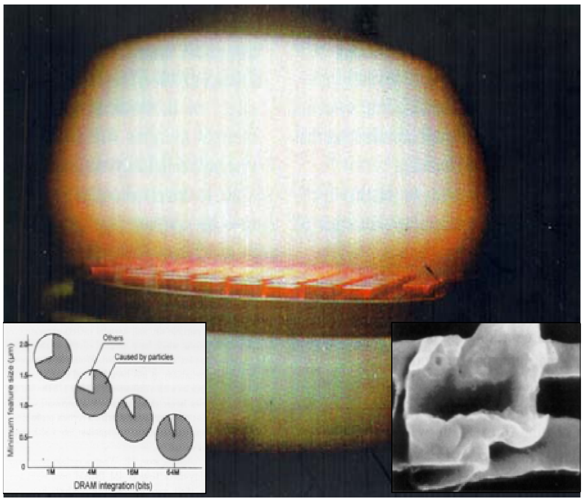
$$\begin{aligned} I_e &= \sqrt{8\pi} a^2 n_e \upsilon_{T_e} \exp\left(e\varphi_s / k_B T_e\right), \\ I_i &= \sqrt{8\pi} a^2 n_i \upsilon_{T_i} \exp\left(1 - e\varphi_s / k_B T_i\right) \end{aligned} \tag{8}$$

It should be noted that the stationary potential of the dust particle surface (floating potential) is determined by the balance of electron and ion fluxes collected by the particle:

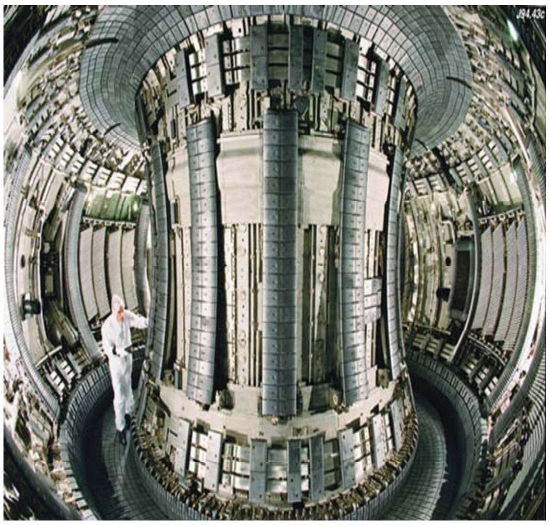
$$I_e = I_i \tag{9}$$

The range of existence of nonideal dusty plasma (in the nature, laboratory and technology)

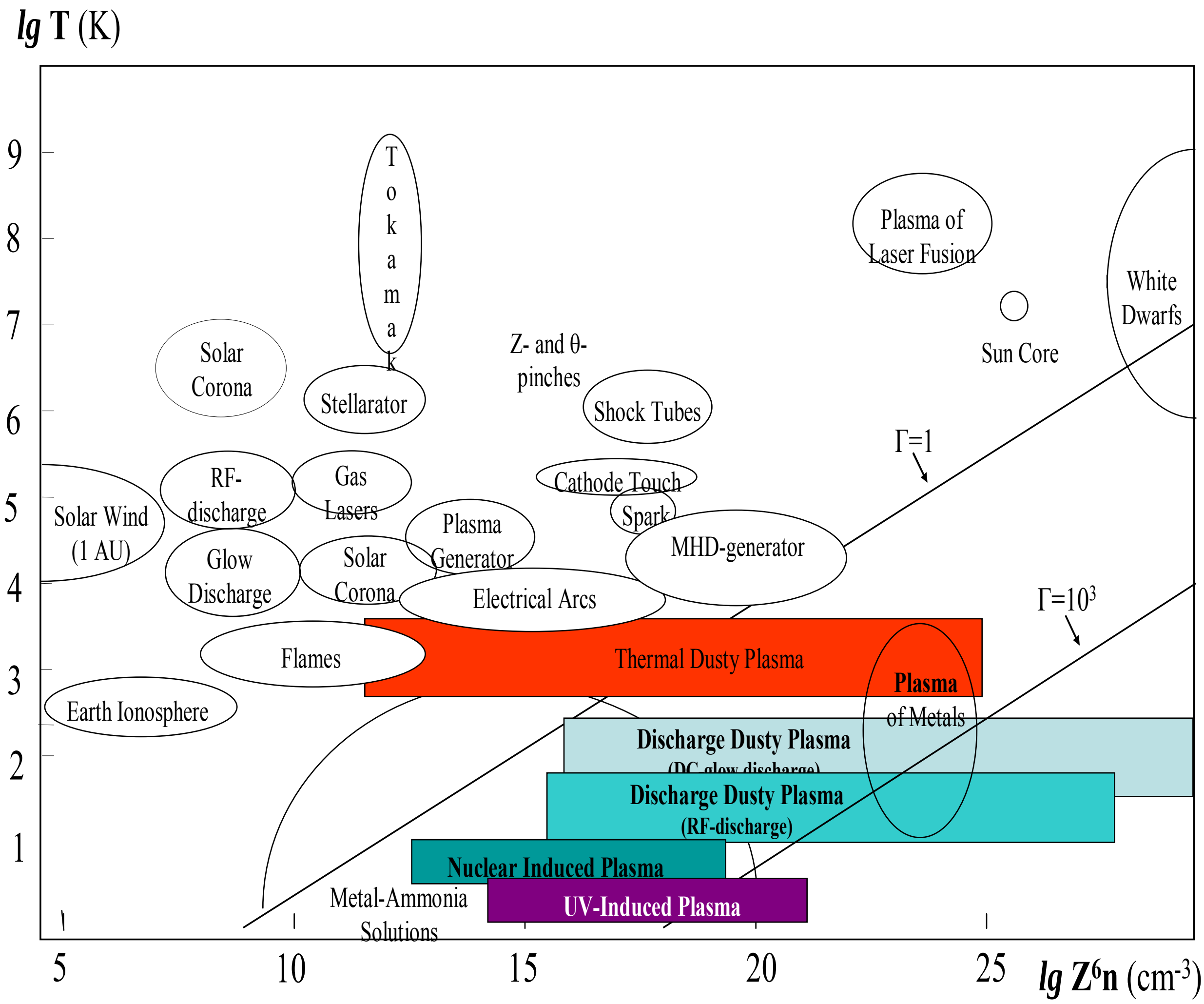




Microelectronic devices with plasma technology



Thermonuclear devices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Tokamak
Plasma of Laser Fusion
Sun Core
White Dwarfs
Solar Corona
Stellarator
Z- and θ-pinches
Shock Tubes
Γ=1
Solar Wind (1 AU)
RF-discharge
Gas Lasers
Cathode Touch
Spark
Plasma Generator
MHD-generator
Glow Discharge
Solar Corona
Electrical Arcs
Γ=10³
Flames
Thermal Dusty Plasma
Plasma of Metals
Earth Ionosphere
Discharge Dusty Plasma
(DC glow discharge)
Discharge Dusty Plasma
(RF-discharge)
Nuclear Induced Plasma
UV-Induced Plasma
Metal-Ammonia Solutions