

Behavior of Dust in Tokamak Devices

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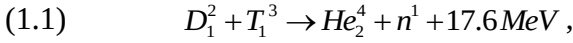
Abstract: Over the past decade, dust particulate contamination has increasingly become an area of concern within the fusion research community. In a burning plasma machine design like the International Thermonuclear Experimental Reactor (ITER), dust contamination presents problems for diagnostic integration safety issues. Additionally, due to ITER design, such dust contamination problems are projected to become of even greater concern due to dust/wall interactions and possible instabilities created within the plasma by such particulates. Since the dynamics of such dust can in general be explained employing a combination of the ion drag, Coulomb force, and ion pre-sheath drifts.

Keywords: Nuclear Fusion, Tokamak, Dusty Plasma, Dust Debye Shielding, Fusion Reactors Safety.

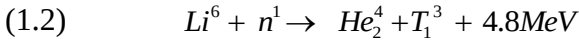
1. Nuclear Fusion at a Glance

If our scientist, researcher, eminent scholars are succussed in controlled nuclear fusion i.e. creation of plasma on an industrial scale, is undoubtedly the most attractive. The reason, it provides pollution free, low cost energy with zero Carbon emissions. Nuclear fusion is the fusing of two small nuclei to form a larger one with an accompanying release of energy arising from the conversion of mass to binding energy. In order to achieve fusion a critical triple product of density, temperature and pressure must be satisfied. There are three confinement approaches to maximize this product, namely gravitational confinement, inertial confinement and magnetic confinement. Deuterium is relatively abundant, being present with a concentration of 156ppm in naturally occurring Hydrogen. Deuterium-Tritium (D-T) reaction through equation (1.1) releases 17.6 MeV and

Tritium is scarce and must be bred using Lithium and releases through equation (1.2) 4.8 MeV.



Similarly



The most promising nuclear fusion device is the 'Tokamak', a magnetic confinement device. In Tokamak conditions, the fuel must be heated to around $100 \times 10^6 \text{ K}$ and on this temperature scale, the fuel exists in the plasma state. The plasma is so hot that any solid material coming into contact with it would be instantly vaporized and so the plasma must be contained by magnetic fields. Considering the Fusion reaction only, the Tokamak is an inherently safe device since at one time, only a few grams of fuel is present in the reactor, so there is no chance of a runaway reaction. This also means the reactor could be shut down very rapidly unlike a fission plant. Such safety claims are widely proliferated by Tokamak researchers. Now we see the behavior of dust in the device¹.

2. Dust in Fusion Devices

The Tokamak (the fusion device) consists of a Torus shaped reactor vessel and a metallic core, figure 1. The plasma within the reactor vessel acts just like a secondary winding on an ordinary transformer, and the configuration allows large currents to be induced in the plasma. The plasma is subsequently heated by the ohmic effect. Further heating is achieved by the injection of neutral particles (NBI), and/or by radio frequency. Together, these methods one can take the temperature of the core up to around $150 \times 10^6 \text{ K}$.

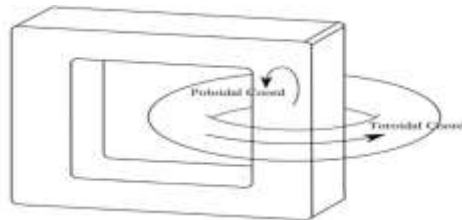


Figure 1. Schematic of Tokamak (Fusion Device) Geometry Illustrating the Toroidal and Poloidal Directions²

In 1929 Tonks and Langmuir first used the term ‘plasma’ to describe the inner region (remote from the boundaries) of a glowing ionized gas produced by means of an electric discharge in a tube. The term plasma represents a macroscopically neutral gas containing many interacting charged particles (electrons and ions) and neutrals. It is likely that 99% of the matter in our universe (in which the dust is one of the omnipresent ingredients) is in the form of a plasma. The plasma is confined within the vessel by a helical magnetic field consisting of nested flux surfaces upon which particles are transported freely but across which transport is strongly suppressed. The helical confinement field is produced by a superposition between the plasma’s own poloidal magnetic field and a toroidal magnetic field, generated via external current coils².

Dust is produced in tokamaks by the interaction between the plasma and the plasma facing components. Dust has not yet been of a major concern in existing tokamaks if the dust quantity is small. However, in ITER and in future reactors, it will represent operational and potential safety issues. From a safety point of view, in order to control the potential dust hazard, the current ITER strategy is based on a defense in depth approach designed to provide reliable confinement systems, to avoid failures, and to measure and minimize the dust inventory. In addition, R&D (research and development) is put in place for optimization of the proposed methods, such as improvement of measurement, dust cleaning and the reduction of dust production. The aim of the paper to see the behavior of the dust during experimental operations³.

In most cases a plasma coexists with the dust particulates. These particulates may be as large as a micron. They are not neutral, but are charged either negatively or positively depending on their surrounding plasma environments. An admixture of such charged dust or macro-particles, electrons, ions and neutrals form a ‘dusty plasma’. It is also known as ‘complex plasma’. The study of complex plasmas has been of increasing importance over recent years with a need for a common experimental apparatus recognized in the late 1980s⁴.

The boundary between the closed field lines that make up the nested flux surfaces and the open field lines, which end on material targets in the vessel, is called the separatrix in Divertor Tokamaks. The Divertor consists of a magnetic field configuration along with material targets, Divertor plates, which prevent the hot plasma from coming into contact with the first wall of the reactor vessel, thereby maximizing reactor life. The region of open field lines is known as the scrape off layer (SOL), and it is here that so

called 'dust' particles are found. The scrape off layer is at a much lower temperature than the core, and any dust grains transported to the core are immediately vaporized. The magnetic field configuration is illustrated by the schematic poloidal cross section through a reactor vessel.

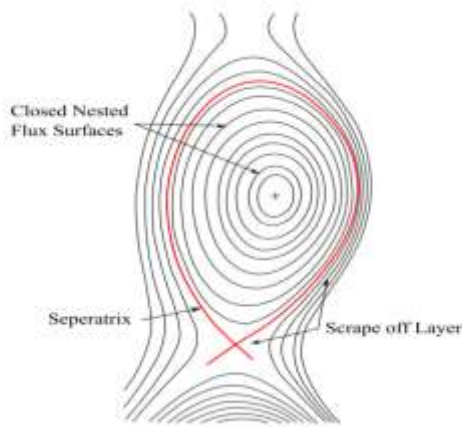


Figure 2. Schematic of a poloidal cross section through a Tokamak showing the nested poloidal flux surfaces, the scrape off layer (SOL), the plasma edge and the last closed flux surface⁵.

3. Characteristics of Dusty Plasmas

Dusty plasmas are low-temperature fully or partially ionized electrically conducting gases whose constituents are electrons, ions, charged dust grains and neutral atoms. Dust grains are massive (billions times heavier than the protons) and their sizes range from nanometers to micrometers. Dust grains may be metallic, conducting, or made of ice particulates. The size and shape of dust grains be different. However, when viewed from afar, they can be considered as point charges. A plasma with dust particles or grains can be termed as either 'dust in a plasma' or 'a dusty plasma', depending on the ordering of a number of characteristic lengths.

The symbols are as follows : dust grain radius (r_d), the average inter-grain distance (a), the plasma Debye radius (λ_D). If the situation $r_d \ll \lambda_D < a$ then there is 'dust in a plasma', while the situation occurs $r_d \ll a < \lambda_D$ then there is 'a dusty plasma'.

When we consider a plasma with isolated dust grains ($a \gg \lambda_D$), we should take into account the local plasma inhomogeneities. On the other hand, when we consider the opposite situation ($a \ll \lambda_D$), we should treat

dust grains as massive charged particles, similar to multiply charged negative or positive ions. However, in studies of collective dusty plasma behavior, we should also take into account the dust particle charging processes. The basic differences between an electron–ion (or multi-ion) plasma and a dusty plasma are mentioned in table 1. The table shows that there exists some distribution for the dust grain charge-mass ratio (q_d/m_d).

Table 1. The basic differences between electron–ion and dusty plasma.

Characteristics	Electron–ion plasma	Dusty plasma
Quasi-neutrality condition	$n_{e0} = Z_i n_{i0}$	$Z_d n_{d0} + n_{e0} = Z_i n_{i0}$
Massive particle charge	$q_i = Z_i e$	$ q_d = Z_d e \gg q_i$
Charge dynamics	$q_i = \text{constant}$	$\partial q_d / \partial t = \text{net current}$
Massive particle mass	m_i	$m_d \gg m_i$
Plasma frequency	ω_{pi}	$\omega_{pd} \ll \omega_{pi}$
Debye radius	λ_{De}	$\lambda_{Di} \ll \lambda_{De}$
Particle size	uniform	dust size distribution
$\mathbf{E} \times \mathbf{B}_0$ particle drift	ion drift at low B_0	dust drift at high B_0
Interaction	repulsive only	attractive between grains
Crystallization	no crystallization	dust crystallization
Phase transition	no phase transition	phase transition

When no external disturbance is present, like an electron–ion plasma a dusty plasma is also macroscopically neutral. This means that in an equilibrium with no external forces present, the net resulting electric charge in a dusty plasma is zero. Therefore, the equilibrium charge neutrality condition in a dusty plasma reads

$$(3.1) \quad q_i n_{i0} = e n_{e0} - q_d n_{d0}$$

n_{s0} is the unperturbed number density of the plasma species s (s equals e for electrons, i for ions and d for dust grains), $q_i = Z_i e$ is the ion charge, $q_d = Z_d e$ ($-Z_d e$) is the dust particle charge when the grains are positively (negatively) charged, e is the magnitude of the electron charge and Z_d is the number of charges residing on the dust grain surface. Typically, a dust grain acquires one thousand to several hundred thousand elementary charges and $Z_d n_{d0}$ could be comparable to n_{i0} , even for $n_{d0} \ll n_{i0}$. Accordingly, for negatively charged dust grains equation (3.1) is then replaced by

$$(3.2) \quad n_{i0} \approx Z_d n_{d0}$$

It should be noted here that a complete depletion of the electrons is not possible, because the minimum value of the ratio between the electron and ion number densities turns out to be the square root of the electron to ion mass ratio when electron and ion temperatures are approximately equal and the grain surface potential approaches zero².

4. Debye Shielding

It is well known that a fundamental characteristic of a plasma is its ability to shield the electric field of an individual charged particle or of a surface that is at some non-zero potential. This characteristic provides a measure of the distance (called the Debye radius) over which the influence of the electric field of an individual charged particle (or of a surface that has a non-zero potential) is felt by other charged particles inside the plasma. The Debye shielding in a dusty plasma is explained below.

Let us assume that an electric field is applied by inserting a charged ball inside a dusty plasma, whose constituents are electrons, ions and positively or negatively charged dust particles. The ball would attract particles of opposite charges, i.e. if it is positive, a cloud of electrons and dust particles (if they are negatively charged) would surround it, and if it is negative, a cloud of ions and dust particles (if they are positively charged) would surround it. We also assume that recombination of the plasma particles does not occur on the surface of the ball. If the plasmas were cold (i.e. there were no agitations of charged particles), there would be just as many charges in the cloud as in the ball. This case corresponds to a perfect shielding, i.e. no electric field would be present in the body of the plasma outside the cloud. On the other hand, if the temperature is finite, those particles which are at the edge of the cloud (where the electric field is weak) would have enough thermal energy to escape from the cloud. The edge of the cloud then occurs at the radius where the potential energy is approximately equal to the thermal energy $k_B T_s$ of the particles (where k_B is the Boltzmann constant and T_s is the temperature of the plasma species s). This corresponds to an incomplete shielding and a finite electric potential exists there. We now calculate an approximate thickness of such a charged cloud (sheath). We assume that the potential $\varphi_s(r)$ at the center ($r = 0$) of the cloud is φ_{s0} . We also assume that the dust-ion mass ratio m_d/m_i is so large that the inertia of the dust particles prevents them from moving significantly. The massive dust particles form only a uniform background of negative charges. The electrons and ions are assumed to be in local

thermodynamic equilibrium, and their number densities, n_e and n_i , obey the Boltzmann distribution, namely

$$(4.1) \quad n_e = n_{e0} \exp (e \varphi_s / (k_B T_e)),$$

and

$$(4.2) \quad n_i = n_{i0} \exp (-e \varphi_s / (k_B T_i)),$$

where n_{e0} and n_{i0} are, respectively, the electron and ion number densities far away from the cloud. For our present dusty plasma situation, Poisson's equation can be written in the form

$$(4.3) \quad \nabla^2 \varphi_s = 4\pi (e n_e - e n_i - q_d n_d),$$

where n_d is the dust particle number density.

According to our assumption, the dust particle number density is the same both inside and outside the cloud, i.e.

$$(4.4) \quad q_d n_d = q_d n_{d0} = e n_{e0} - e n_{i0},$$

$$(4.5) \quad e\varphi_s / (k_B T_e) \ll 1,$$

and

$$(4.6) \quad e\varphi_s / (k_B T_i) \ll 1,$$

substituting the value of equation (4.4) in equation (4.3) we get,

$$(4.7) \quad \nabla^2 \varphi_s = 4\pi (e n_e - e n_i - e n_{e0} + e n_{i0}),$$

using equations (4.5) and (4.6) we get,

$$(4.8) \quad \nabla^2 \varphi_s = 4\pi e \left[n_{e0} \{ \exp (e \varphi_s / (k_B T_e)) - 1 \} + n_{i0} \{ 1 - \exp (-e \varphi_s / (k_B T_i)) \} \right],$$

by expanding (4.8) and ignoring higher order terms and using equation (4.5), (4.6) we get,

$$(4.9) \quad \nabla^2 \varphi_s = 4\pi e^2 \left[\{ n_{e0} / (k_B T_e) \} + \{ n_{i0} / (k_B T_i) \} \right] \varphi_s$$

$$(4.10) \quad \nabla^2 \varphi_s = (1/\lambda_{De}^2 + 1/\lambda_{Di}^2) \varphi_s,$$

where $\lambda_{De} = (k_B T_e / 4\pi n_{e0} e^2)^{1/2}$ and $\lambda_{Di} = (k_B T_i / 4\pi n_{i0} e^2)^{1/2}$ are the electron and ion Debye radii, respectively. It should be noted here that the approximations $e\varphi_s / (k_B T_e) \ll 1$ and $e\varphi_s / (k_B T_i) \ll 1$ may not be valid near the region $r = 0$. However, this region (called the sheath), where the potential φ_s falls very rapidly, does not contribute much to the thickness of the cloud. Assuming $\varphi_s = \varphi_{s0} \exp(-r/\lambda_D)$, we obtain from equation (4.10) the dusty plasma Debye radius

$$(4.11) \quad \lambda_D = \lambda_{De} \lambda_{Di} / (\lambda_{De}^2 + \lambda_{Di}^2)^{1/2}.$$

The quantity λ_D is a measure of the shielding distance or the thickness of the sheath. For a dusty plasma with negatively charged dust grains, we have $n_{e0} \ll n_{i0}$ and $T_e \geq T_i$, i.e. $\lambda_{De} \gg \lambda_{Di}$. Accordingly, we have $\lambda_D \approx \lambda_{Di}$. This means that the shielding distance or the thickness of the sheath in a dusty plasma is mainly determined by the temperature and number density of the ions. However, when the dust particles are positively charged and most of the ions are attached onto the dust grain surface, i.e. when $T_e n_{i0} \ll T_i n_{e0}$, we have $\lambda_{De} \approx \lambda_{Di}$. This corresponds to $\lambda_D \approx \lambda_{De}$. This means that in a dusty plasma with positively charged dust grains, the shielding distance or the thickness of the sheath is mainly determined by the temperature and density of the electrons².

5. Characteristic Frequencies

Similar to the usual electron-ion plasma, an important dusty plasma property is the stability of its macroscopic space charge neutrality. When a plasma is instantaneously disturbed from its equilibrium, the resulting internal space charge field gives rise to collective particle motions, which tend to restore the original charge neutrality. These collective motions are characterized by a natural frequency of oscillations known as the plasma frequency ω_p . We now explain how one can define the plasma frequency ω_p in a uniform, cold, unmagnetized dusty plasma. The electrostatic oscillations of the electrons, ions or dust particles, which are due to the internal space charge field are described by the equation of continuity,

$$(5.1) \quad \frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{v}_s) = 0$$

the equation of momentum,

$$(5.2) \quad \frac{\partial \mathbf{v}_s}{\partial t} + (\mathbf{v}_s \cdot \nabla) \mathbf{v}_s = -(q_s / m_s) \nabla \varphi ,$$

and Poisson's equation,

$$(5.3) \quad \nabla^2 \varphi = -4\pi \sum_s q_s n_s ,$$

here, for simplicity, we have neglected sources and sinks as well as the pressure gradient forces. We now assume that the amplitude of the oscillations is so small that the terms containing higher powers of the amplitude can be neglected and that at the equilibrium all plasma particles (electrons, ions and dust particles) are at rest and no equilibrium space charge field is present. Therefore, assuming $n_s = n_{s0} + n_{s1}$, where $n_{s1} \ll n_{s0}$, we can linearize equations (5.1)-(5.3), and combine them to obtain,

$$(5.4) \quad \frac{\partial^2}{\partial t^2} \nabla^2 \varphi + 4\pi \sum_s \frac{n_{s0} q_s^2}{m_s} \nabla^2 \varphi = 0 .$$

Integrating equation (5.4) over the space $r(x, y, z)$ twice under the appropriate boundary condition [namely $\varphi = 0$ at equilibrium ($r = 0$)], and replacing $\partial/\partial t$ by d/dt we can rewrite equation (5.4) as

$$(5.5) \quad \frac{\partial^2 \varphi}{\partial t^2} + \omega_p^2 \varphi = 0 ,$$

where

$$(5.6) \quad \omega_p^2 = 4\pi \sum_s \frac{n_{s0} q_s^2}{m_s} = \omega_{ps}^2 ,$$

And $\omega_{ps} = (4\pi n_{s0} q_s^2 / m_s)^{1/2}$ represents the plasma frequency associated with the plasma species s . Equation (5.6) indicates that the internal space charge potential oscillates with a characteristic frequency ω_p . This can be interpreted as follows. When the plasma particles are displaced from their equilibrium positions, a space charge field will be built up in such a direction as to restore the neutrality of the plasma by pulling the particles back to their original positions. But because of their inertia, they will

overshoot and will be again pulled back to their original positions by the space charge field of the opposite polarity. Again, because of their inertia they will overshoot and thus continuously oscillate around their equilibrium positions. The frequency of such oscillations will, of course, not be the same for electrons, ions and dust grains, but will depend on the mass and the charge of the plasma particles. For example, electrons oscillate around ions with the electron plasma frequency

$$(5.7) \quad \omega_{pe} = (4\pi n_{e0} e^2 / m_e)^{1/2}$$

ions oscillate around charged dust grains with the ion plasma frequency,

$$(5.8) \quad \omega_{pi} = (4\pi n_{i0} e^2 / m_i)^{1/2}$$

and dust particles oscillate around their equilibrium positions with the dust plasma frequency,

$$(5.9) \quad \omega_{pd} = (4\pi n_{d0} Z_d^2 e^2 / m_d)^{1/2}.$$

The other important characteristic frequencies are associated with the collisions of the plasma particles (electrons, ions and dust grains) with stationary neutrals. These are the electron–neutral collision frequency ν_{en} , the ion–neutral collision frequency ν_{in} , and the dust–neutral collision frequency ν_{dn} , respectively. The collision frequency ν_{sn} for scattering of the plasma species s by the neutrals is

$$(5.10) \quad \nu_{sn} = n_n \sigma_s^n V_{Ts},$$

where n_n is the neutral number density, σ_s^n is the scattering cross section (which is typically of the order of $5 \times 10^{-15} \text{ cm}^2$ and depends weakly on the temperature T_s) and $V_{Ts} = (k_B T_s / m_s)^{1/2}$ is the thermal speed of the species s . The collisions of the plasma particles with stationary neutrals tend to damp their collective oscillations and gradually diminish their amplitudes. The oscillations will be slightly damped only when the collision frequency ν_{sn} is smaller than the plasma frequency ω_p , i.e.

$$(5.11) \quad \nu_{en}, \nu_{in}, \nu_{dn} < \omega_p.$$

6. Coulomb Coupling Parameter

One other important special characteristic of a dusty plasma is its Coulomb coupling parameter which determines the possibility of the formation of dusty plasma crystals. To explain this characteristic, let us consider two dust grains (both having the same charge q_d) separated from each other by a distance a . The dust Coulomb potential energy (including the shielding effect) is

$$(6.1) \quad \varepsilon_c = \frac{q_d^2}{a} \exp\left(-\frac{a}{\lambda_d}\right),$$

and the dust thermal energy is $k_B T_d$. Thus, the Coulomb coupling parameter Γ_c (defined as the ratio of the dust potential energy to the dust thermal energy) is by

$$(6.2) \quad \Gamma_c = \frac{Z_d^2 \varepsilon^2}{a k_B T_d} \exp\left(-\frac{a}{\lambda_d}\right).$$

A dusty plasma is a weakly coupled system when $\Gamma_c \ll 1$, while it is strongly coupled when $\Gamma_c \gg 1$. Thus, the number of charges residing on the grain surface (Z_d), the ratio of the intergrain distance to the Debye screening radius (a/λ_D) and the dust thermal energy ($k_B T_d$) play decisive roles in deciding whether a dusty plasma will be strongly coupled or weakly coupled. It can easily be shown that in several laboratory dusty plasma systems, massive dust grains are strongly coupled because of their huge electric charge, low temperature and small intergrain distance.

7. Dust-Plasma Interactions

In order to optimize dust removal employing any of the techniques, the dust particulate parameters (i.e., chemical composition, particulate dynamics, size, charge, etc.) must first be known. Although some of this information can be extracted from in-situ measurements. Optical methods involving high-resolution microscopy in order to see the structure of the particle itself have also been used. Interestingly, much of the dust found in fusion environments to date is similar in size, shape and composition to the microspheres commonly used within complex plasma experiments employing a GEC rf Reference cell⁶. The source of the dust found within

fusion systems is also of great interest. Plasma arcing to the containment walls ablates wall material, creating changes in the overall wall geometry. This has the ability to appreciably influence global plasma parameters due both to the resulting imperfections in the boundary conditions and overall contamination of the plasma. It is well known from experiments within the complex plasma community that any dust within a plasma interacts with the surrounding plasma (in complex plasmas, this reaction is large enough that the dust is considered an integral component of the plasma). Many of these interactions may have possible applications within fusion systems. For example, recent GEC rf Reference Cell data suggests that increasing dust production appears to increase conductivity between the plasma and the wall leading to arcing and new dust production. Dust precipitating on surfaces, or crevices created by particle dislodgment can also change the overall engineering design of the chamber impacting both plasma performance and stability. Dust acting as a sink/source within the plasma, also impacts the ion recombination rate and can emit electrons due to photoionization or thermal emission. Dust dynamics within a GEC rf Reference Cell is characterized by a variety of forces. Despite the small size of the particles, gravity plays a critical role in determining the overall dynamics of the dust. Obviously, the charge on the dust (due primarily to electron bombardment and plasma ion flows) also contributes to the final equilibrium symmetry (if any) of levitated dust. Intrinsic characteristics of the experimental chamber such as the rf driving frequency, variable bias, and the operating neutral gas pressure also create fluctuations in the particle.

Finally, particle dynamics within either a reference cell or a fusion device are strongly influenced by thermal forces. The bulk plasma within either system is generally hotter than the walls, facilitating dust and plasma diffusion². Now we see Empirical secondary electron emission through the following formula⁷,

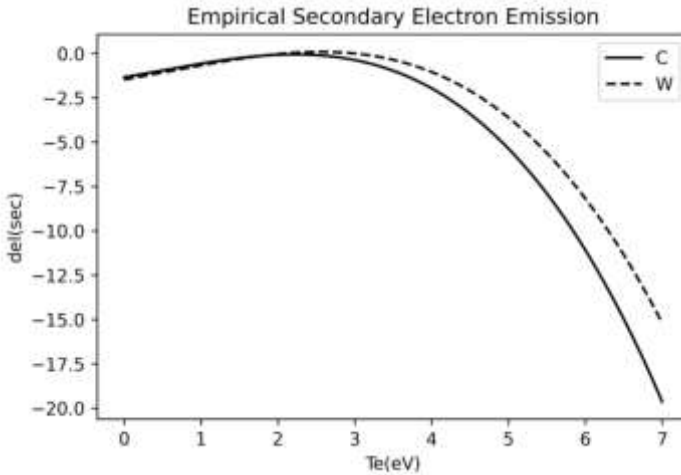
$$(7.1) \quad \log_{10}[\delta_{\text{sec}}(T_e)] = C_3 x^3 + C_2 x^2 + C_1 x + C_0 ,$$

$$(7.2) \quad \log_{10}[\delta_{\text{sec}}(T_e)] = W_3 x^3 + W_2 x^2 + W_1 x + W_0 ,$$

where $x = \log_{10}(T_e)$.

Table 2. Constants for Empirical Electron Emission

C_0	-1.3410	W_0	-1.4755
C_1	0.7428	W_1	0.7240
C_2	0.1149	W_2	0.1521
C_3	-0.0849	W_3	-0.0765

**Figure 3.** Empirical Secondary Electron Emission

8. Conclusion

In this paper I have given the approach of behavior of dust in the plasma. The behavior of dust could not be ignored in the plasma parameters. The observations have been done using the species s , which involve for electrons, ions and dust. Basic equations with approximations are used for the species s .

References

1. Christopher. M. Bray, *Dust Grain Charging in Tokamak Plasmas*, Department of Physics, Imperial College London, September 2014.
2. P. K. Shukla, *Series in Plasma Physics, Introduction to Dusty Plasma Physics*, Ruhr-Universitat Bochum, Germany and Ume University, Sweden A A Mamun Jahangrinagar University, Dhaka, Bangladesh, Institute of Physics Publishing Bristol and Philadelphia, ISBN 0 7503 0653 X. IOP Publishing Ltd 2002.
3. *Journal of Nuclear Materials*, **390-391** (2009), 57-60, . <https://www.sciencedirect.com/science/journal/00223115coating> 2003.

4. V. E. Fortov, A. V. Ivlev, A. G. Khrapak and G. E. Morfill. Complex (Dusty) Plasmas: Current Status, Open Issues, Perspectives, *Physics Reports*, **421(1-2)** (2005), 1-103.
5. SOL image. From website.
6. The Gaseous Electronics Conference RF Reference Cell, *J. Res. Natl. Inst. Stand. Technol.*, **100** (1995), 327.
7. Minas Bacharis, et al, Dust in Tokamak: An Overview of the physical model of the dust in tokamak code, *Physics of Plasmas*, **17** (2010), 042505.