Positive Tungsten Dust In Tokamaks

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Abstract. This paper discusses adapting the OML model to estimate the floating potential of dust grains where secondary electron emission is a significant charging mechanism, making it applicable to tungsten dust in tokamaks.

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INTRODUCTION

The floating potential attained by a spherical collector in a plasma is a fundamental problem. The collector is usually considered to be charged only by collection of plasma particles. As the electrons are more mobile than the ions, the particle usually charges negatively. Orbital motion limited theory (OML) [1], is the most widely used theory due to its ease of use.

In hotter plasmas, e.g. tokamaks, secondary electron emission needs to be considered. Secondary electron yields can exceed unity for various materials, meaning that the dust grain charges positively. In addition, for very small objects, the yield can be much greater than unity due to the relatively small amount of material the electrons have to pass though to escape. Situations where the dust is charged positively will affect the particles temperature by altering the expected ion and electron fluxes.

This paper considers developing a theory based on the OML theory.

REVIEW OF OML

The electrons around a negatively charged object of radius a can be considered to have a Maxwell-Boltzmann distribution, and therefore the current is

$$I_e = 4\pi a^2 \frac{1}{4} n_0 \exp\left(\frac{e\phi}{k_B T_e}\right)\overline{v_e} \tag{1}$$

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where n_0 is the density of the bulk plasma, ϕ is the potential on the dust, T_e is the electron temperature and $\overline{v_e}$ is the electron thermal speed. Currents are given normalized to the charge of the species. The ions are assumed to have a cross-section for collection derived from conservation of energy and angular momentum, where the limiting orbit is one that grazes the grain surface. For a Maxwellian distribution of ions in the bulk plasma the ion current is

$$I_i = 4\pi a^2 \frac{1}{4} n_0 \left(1 - \frac{e\phi}{k_B T_i}\right) \overline{v_i} \tag{2}$$

Equating these currents gives an expression for the floating potential, which after normalisation looks like

$$\exp(V) = \sqrt{\frac{\theta}{\mu}} \left(1 - \frac{V}{\theta}\right) \tag{3}$$

where $V = e\phi/(k_B T_e)$, $\theta = T_i/T_e$, and $\mu = m_i/m_e$.

SECONDARY YIELD < 1

For this problem we can simply modify the OML equation previously derived. We assume the electron current is reduced by the secondary yield as there is no trapping of secondaries by the field structure. The OML equation becomes [2]

$$(1-\delta)\exp(V) = \sqrt{\frac{\theta}{\mu}} \left(1 - \frac{V}{\theta}\right). \tag{4}$$

Results are shown in figure 1. As one would expect, the secondary electron yield reduces the potential predicted by the non-modified OML theory. As the yield gets close to unity, positive potentials are achieved. This is impossible with the currents we have derived, and shows the model is breaking down. In reality, there may be trapping of secondaries by the field structure.

SECONDARY YIELD > 1

When the yield exceeds unity, the dust grain will charge positively. This alters the expressions for the currents we have used up to this point. Depending on the temperature and density of the secondary electrons, they may dominate the shielding process. For this to occur, the secondary electrons must be trapped by the electric field structure. Indeed, in simulations [3] a potential well has been observed.

We need to quantify the shielding process somehow. As we have two populations of electrons, there will be two shielding (Debye) lengths $\lambda_{D\sec}$ and λ_D, where the subscript sec denotes secondaries.

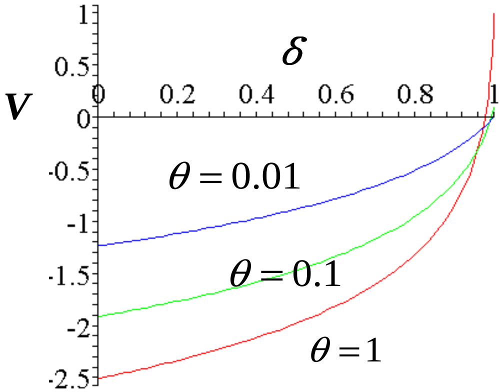

FIGURE 1. Floating potential as a function of δ for different values of θ.

The Case Of A Potential Minimum

If $\lambda_{D\sec} < \lambda_D$, a potential well may be formed. The radius where the potential minimum occurs will be denoted as *b*. We can consider the current balance of primary and secondary electrons and ions to derive a floating condition at the grain radius *a* $I_i(a) + I_e(a) - I_{\sec}^{out}(a) + I_{\sec}^{in}(a) = 0$, along with a secondary electron relation $I_{\sec}^{out}(a) = \delta I_e(a)$. We will assume that secondary electrons are produced with a Maxwellian distribution. As they are in a repulsive potential their density can be given by a Boltzmann factor between *a* and *b*. The floating condition becomes

$$I_i = I_e\left(1 - \frac{b^2}{a^2}\delta \exp\left(-\frac{\phi_a - \phi_b}{k_B T_{\sec}}\right)\right). \tag{5}$$

We now need to quantify the ion and electron currents. To keep the model simple, we assume the ion density obeys a Boltzmann relation and the electron motion is orbit limited between *b* and *a*. The floating condition now becomes

$$\frac{\exp(-\Delta V/\theta)}{(1+\Delta V)}\frac{n_i(b)\overline{v_i}(b)}{n_e(b)\overline{v_e}(b)} = 1 - \frac{b^2}{a^2}\delta \exp(-\Delta V \sigma) \tag{6}$$

where $\Delta V = \frac{e(\phi_a - \phi_b)}{k_B T_e}$ and $\sigma = \frac{T_e}{T_{sec}}$. The ion and electron fluxes now need to be defined.

The easiest problem to solve is the case where a >> $\lambda_{D\sec}$. In this case we can set *a* ≈ *b*, and ignore the OML factor for the electron current. We assume a plasma solution outside *b* so that $n_i(b) = n_e(b)$. The potential at the minimum is $-0.5k_BT_e/e$ for this case. Results for various values of σ with δ = 1.4 (a value typical for tungsten) are shown in figure 2. We see that the potential difference between *a* and *b* decreases as σ increases. The value of ΔV for typical fusion parameters (σ = 20) is small at 0.02. However, for very small particles δ could be far greater, and the potential may differ more radically.

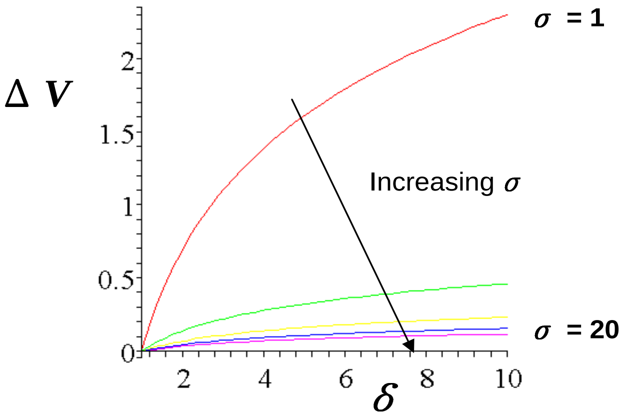

FIGURE 2. Potential difference for different electron temperature ratios.

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