CHARGING OF DUST IN A NEGATIVE ION PLASMA

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ABSTRACT

We investigate experimentally the charging of dust particles in a plasma consisting of positive ions, negative ions and electrons. In typical laboratory plasmas containing electrons and positive ions, dust grains acquire a negative charge. In negative ion plasmas, charging due to the negative ions, in addition to positive ions and electrons, must be taken into account. Calculations show that if a significant fraction of the electrons are attached to negative ions, the magnitude of the charge on the dust particles is reduced. If the ratio $p = n_e/n_+$ of the electron density to positive ion density is sufficiently small and the positive ions are lighter than the negative ions, then the dust charge can be positive. This possibility is investigated in Q-machine plasma operating with potassium ions, and in which the highly electronegative gas SF_6 is added which attaches low energy electrons to produce the SF_6^- negative ion. The relatively cold electrons in the Q-machine plasma (T_e = 0.2 eV) enhances the attachment probability allowing values of $p < 10^{-3}$ to be attained.

The charge on a dust grain in a negative ion plasma

1. Parameters

Consider an *isolated* spherical dust grain of radius a introduced into a plasma consisting of electrons of density n_e, singly charged positive ions of density n_+, and singly charged negative ions of density n_-. Define

$$\varepsilon \equiv \frac{n_-}{n_+}$$

as the fraction of negative ions relative to positive ions. Using the charge neutrality condition

$$n_+ = n_e + n_-$$

we have that:

$$\frac{n_e}{n_+} = 1 - \varepsilon$$

The temperatures of the positive ions, electrons and negative ions are T_+, T_e and T_- respectively.

2. Currents to the dusty grain.

The electron, negative ion and positive ion currents to the dust grain of radius a are given by :

$$I_e = I_{eo} \times \begin{cases} 1 + eV_s/kT_e & V_s > 0 \\ e^{eV_s/kT_e} & V_s < 0 \end{cases}$$

$$I_- = I_{-o} \times \begin{cases} 1 + eV_s/kT_- & V_s > 0 \\ e^{eV_s/kT_-} & V_s < 0 \end{cases}$$

$$I_+ = I_{+o} \times \begin{cases} e^{-eV_s/kT_+} & V_s > 0 \\ 1 - eV_s/kT_+ & V_s < 0 \end{cases}$$

where $$I_{jo} = q_j n_j \left(\frac{kT_j}{m_j}\right)^{1/2} \pi a^2$$

V_S is the potential of the dust grain relative to the plasma. The grain surface potential is then obtained by requiring

$$I_+ + I_e + I_- = 0$$

We give an give an example to show under what conditions one could obtain positively charged grains in such a plasma. For simplicity, consider the case where all species are at the same temperatures $T_+ = T_e = T_- = T$, and define the normalized surface potential

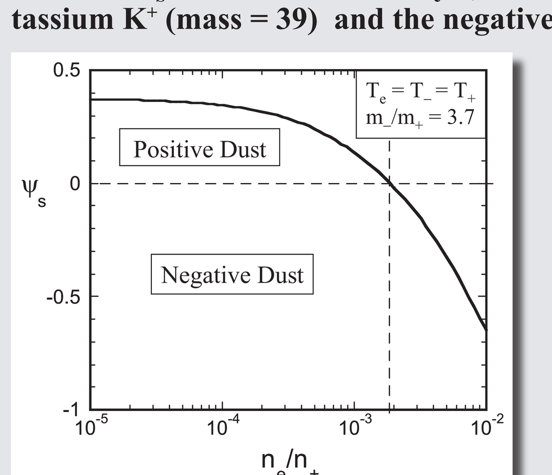
$$\psi_S = eV_S / kT$$

we obtain

$$(1-\varepsilon)\sqrt{\frac{m_+}{m_e}} + \varepsilon\sqrt{\frac{m_+}{m_-}} = \begin{cases} \dfrac{e^{-\psi_s}}{1+\psi_s} & \psi_s > 0 \\ \dfrac{1-\psi_s}{e^{\psi_s}} & \psi_s < 0 \end{cases}$$

This equation can be solved numerically for ψ_S.

A plot of ψ_S vs. the parameter n_e/n_+ for the case in which the positive ion is potassium K^+ (mass = 39) and the negative ion is SF_6^- (mass = 146).



Notice that the positive ion is the *lighter* species.

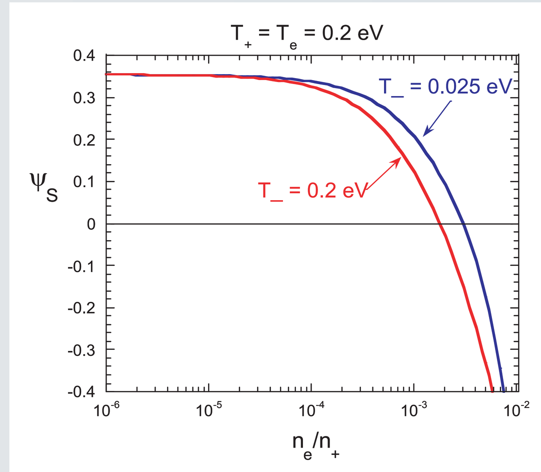
Thus in the presence of a heavy (compared to the + ion) negative ion, the charge on the dust is reduced, and for $n_e/n_+ < 2 \times 10^{-3}$ the dust surface potential (and charge) can be **positive**.

Once the dust surface potential is determined, the charge on the dust is computed using

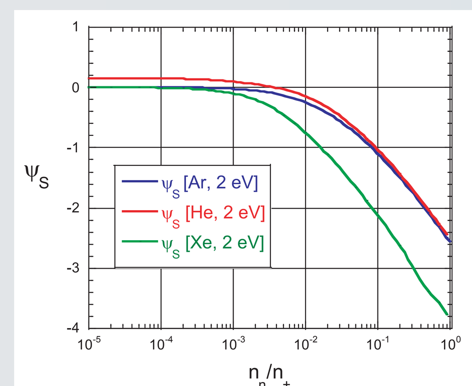
$$Q = 4\pi\varepsilon_0 a V_S$$

3. Effect of temperature ratios

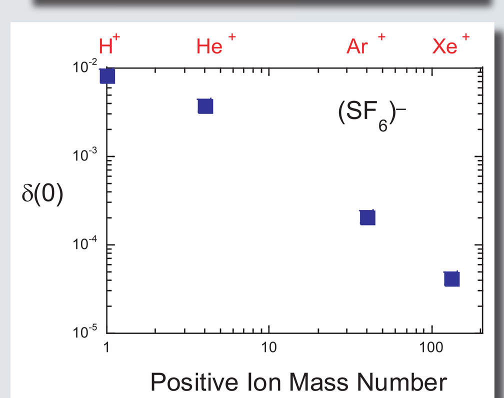
The plot below shows calculations of the normalize dust potential in a negative ion plasma for T_- = 0.2 and 0.025 eV.



4. Effect of positive ion mass.

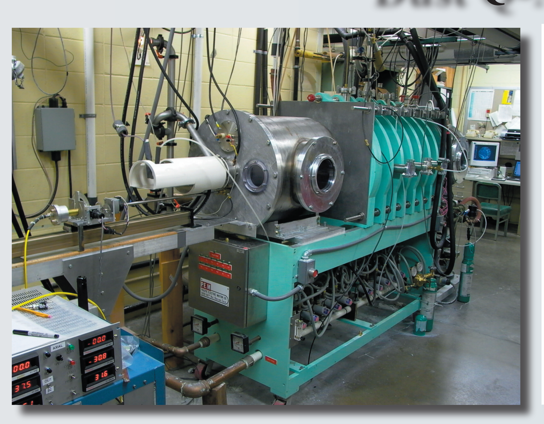


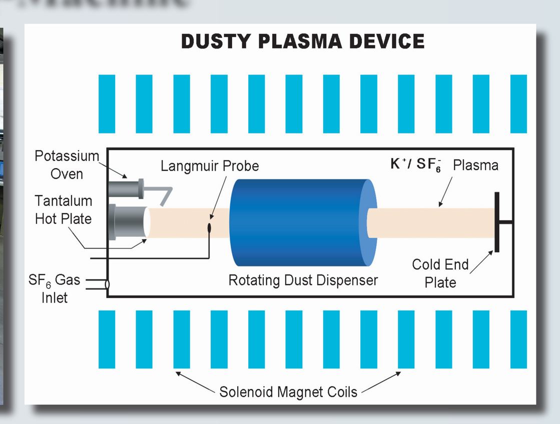
As another example, we show a plot of the normalized dust surface potential for the case of a discharge plasma which can operate in He, Ar, or Xe gasses.



A plot of the quantity δ(0) which is the value of $\delta = n_e/n_+$ for which $\psi_S = 0$, i.e., the dust charge is 0, versus the positive ion mass number.

Dust Q-Machine





The Dust Dispersal Device

- Dust is introduced into the plasma using the rotating cylinder dust dispersal device that is described in detail in W. Xu, B. Song, R. Merlino and N. D'Angelo, "A dusty plasma device for producing extended, steady state, magnetized dusty plasma columns," Rev. Sci. Instrum. 63, 5266 (1992).
- This device disperses dust into the 6 cm diameter plasma column, over a length of 30 cm.
- The dust particles were hollow glass microspheres (provided by Emerson Cuming).
- The particles had a large size distribution ranging from a few microns up to about 100 microns. Most of the particles (50%) were approximately 35 microns in diameter.

FORMATION OF NEGATIVE ION PLASMAS IN A Q-MACHINE

A negative ion plasma can be formed by attachment of electrons on an electronegative gas such as sulfur hexafluoride SF_6

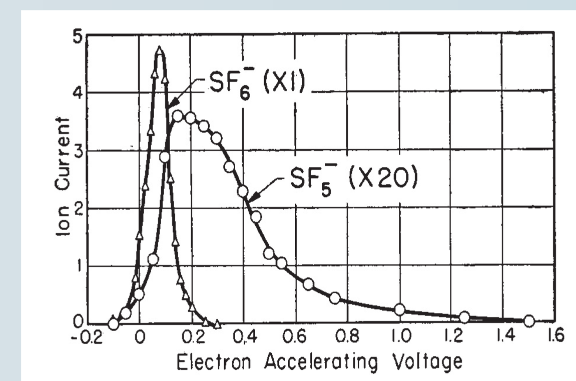
$$e^- + SF_6 \rightarrow SF_6^-$$

The attachment process depends on the electron energy, and favors low energy electrons (tenths of eV's).

The electron temperature in a Q-machine is Te ≈ 0.2 eV, making the Q-machine an ideal device in which to form negative ion plasmas.

An excellent reference on negative ion plasmas:
Sheehan and Rynn, Rev. Sci. Instrum. 59, 1369 (1988).

The electron attachment cross section for SF_6

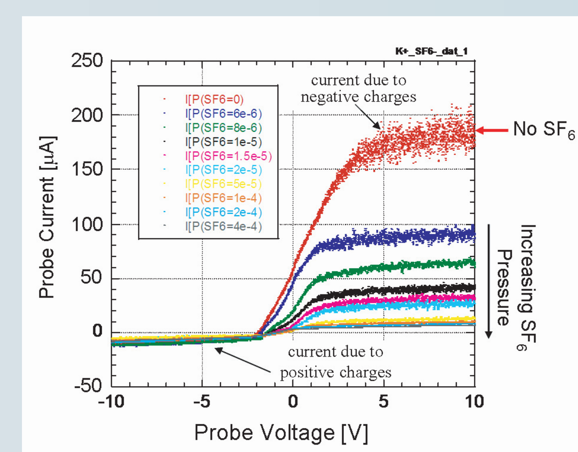


A positive ion/negative ion plasma

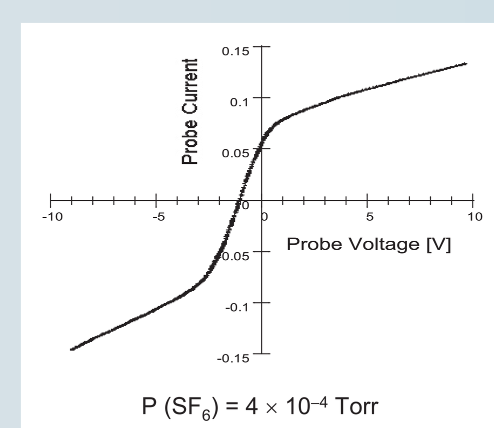
It is possible to have a negative ion plasma in which the electron concentration relative to the positive ions, n_e/n_+ is so small that we are left with essentially a plasma with only positive ions and negative ions.

The effect of negative ion production can be observed using a Langmuir probe. A series of typical Langmuir probe I-V characteristics in a Q machine (K^+) plasma for increasing SF_6 pressures is shown below.

As the SF_6 pressure is increased, increasingly more electrons become attached to form SF_6^- and there is a reduction in the electron current to the probe.

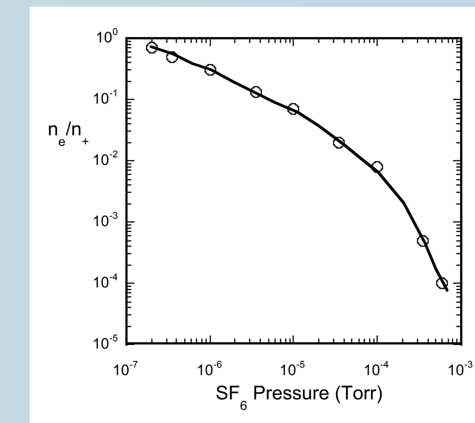


At sufficiently high SF_6 pressures, the Langmuir characteristic is nearly symmetric, indicating that a positive ion/negative ion plasma has been formed.



Determination of the ratio n_e/n_+ in the negative ion plasma

An estimate of the relative concentration of free electrons in the plasma, n_e/n_+ can be made from an analysis of the Langmuir probe characteristic. However, when the electron concentration is very small, probe methods can be inaccurate.

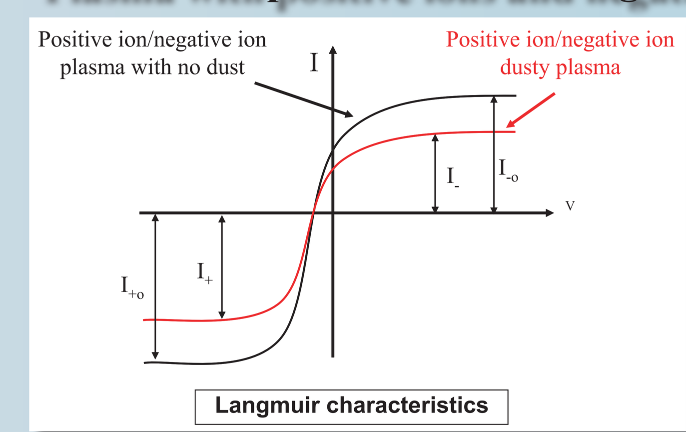


N. Sato[1,2] has shown that n_e/n_+ can be determined by measurements of the propagation characteristics of various electrostatic waves in the negative ion plasma which depend on this quantity. A plot of n_e/n_+ vs. the SF_6 pressure in a potassium ion Q machine is shown below. The parameters of this plot correspond also to our experiments.

⇒ For P(SF_6) ~ 5 × 10^{-4} T, $n_e/n_+ < 10^{-4}$.

1) N. Sato, Plasma Sources, Sci. Technol. 3, 395 (1994).
2) Isikawa et al., J. Phys. Soc. Jpn. 67, 158 (1998)

Plasma with positive ions and negative ions (no electrons)



We assume that sufficient SF_6 has been added to reduce the electron concentration to the point at which electron collection is negligible.

Both positive and negative ions are collected by the dust, so that both probe currents are reduced when the dust is present.

- Before the dust is added the + and – densities are equal: $n_{+o} = n_{-o} = n_o$.
- Densities after dust is added: n_+, n_-
- Neutrality condition: $n_+ + (Q/e)\, n_d = n_-$ [1]

The dust charge Q can be positive or negative. n_d is the dust density.

Solve [1] for $(Q/e)\, n_d$:

$$\frac{Qn_d}{e} = n_- - n_+ \qquad [2]$$

Probe currents per unit area with no dust:

$$I_{+o} = en_{+o}v_+; \quad I_{-o} = en_{-o}v_- \qquad [3]$$

Where v_+, and v_- are the positive and negative ion thermal speeds.

Probe currents per unit area with dust:

$$I_+ = en_+v_+; \quad I_- = en_-v_- \qquad [4]$$

We assume that the thermal speeds are the same with or without the dust.

Using [3] and [4] in [2]

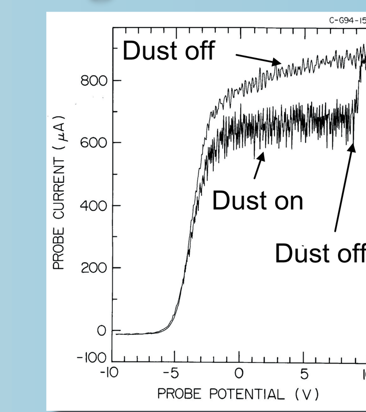
$$\frac{Qn_d}{e} = n_o\left(\frac{I_-}{I_{-o}} - \frac{I_+}{I_{+o}}\right) \qquad [5]$$

Then a Q > 0 (positive dust) implies that

$$\frac{I_-}{I_{-o}} > \frac{I_+}{I_{+o}} \qquad [6]$$

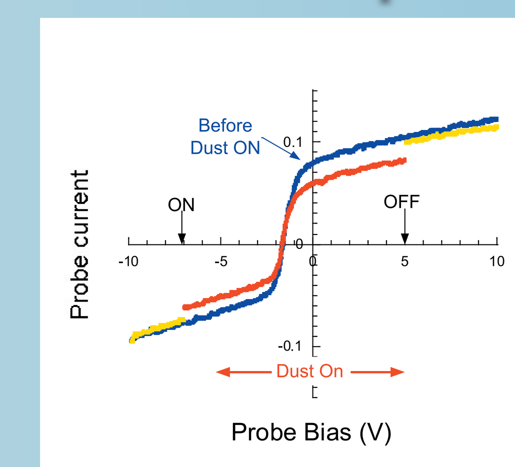
or the fractional reduction in the positive current must be greater than the fractional reduction in negative current.

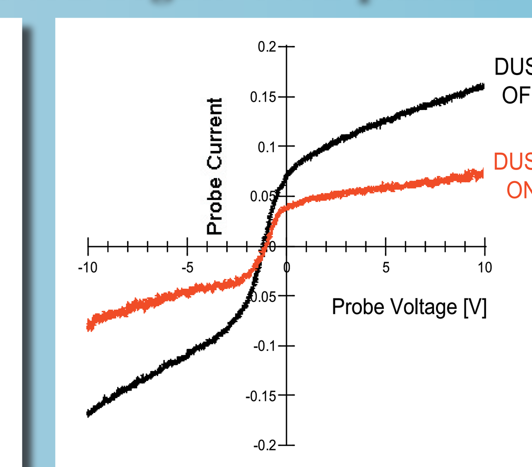
Langmuir Probe characteristic in an e^-/K^+ plasma



A reduction in the electron saturation current is due to the collection of the electrons by the dust particles.

Langmuir probe characteristic with dust introduced into a positive ion/negative ion plasma





Both the negative ion current and positive ion current are reduced when the dust is present.

Experimental evidence for a dusty plasma with positively charged dust?

- At P(SF_6 = 4 × 10^{-4} T), $n_e/n_+ \sim 10^{-4}$.
- According to the dust charging theory, at $n_e/n_+ \sim 10^{-4}$, the normalized dust surface potential, relative to the plasma should be, $\psi_S = eV_S/kT_e \sim +0.3$ → the dust should be positively charged.
- With $T_e = T_+$ = 0.2 eV, and T_- = 0.025 eV, a ψ_S = 0.3, would correspond to a dust charge number, Z ~ (40 – 50) for a dust particle of 1 μm radius.
- According to the probe measurements, $I_-/I_{-0} \approx 0.7$, and $I_+/I_{+0} \approx 0.6$, indicating $Z \gtrsim 0$
- These results are very preliminary.

SUMMARY

- A method for producing *positively charged dust* has been proposed.
- Under normal conditions, dust in laboratory devices is charged negatively due to attachment of the more mobile electrons compared to the positive ions.
- If dust is introduced into a plasma in which a very large percentage of electrons are attached to negative ions, the dust charge Q can be positive, if the positive ion species is the lighter species.
- In principle, the introduction of negative ions into a dusty plasma can result in a *de-charging* of the dust.
- Some preliminary experiments investigating this possibility in a potassium Q machine plasma, have been conducted.

ACKNOWLEDGEMENT

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