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Measurement of the free electrons in a plasma crystal

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In this paper we present a new diagnostics based on the physical concept of the electron plasma resonance and of the plasma sheath resonance. This diagnostic has been applied to a three components complex plasma to provide the density of the free electrons (bound electrons constitute the negative charge of the particles). The density of the free electrons reduces the indetermination of the system and, together with more conventional diagnostics and the modelling of the RF sheath, we have been able to fully characterize the particle assembly.

Derivation of the electron density - The new diagnostic consists in applying an RF voltage, of variable frequency and constant amplitude, to a central small electrode embedded in the grounded electrode of a parallel plate RF reactor, see the experimental apparatus described in [1]. The tuneable RF induces a DC bias that repels the complex plasma levitated in the sheath. The displacement is independent of the frequency in a large range of frequency, see fig. 1, is amplified firstly and later reduces to zero approaching the electron plasma resonance of the crystal. As for the the plasma sheath resonance [2] and the resonance probe [3] the region next to the central electrode and the surrounding area, plasma sheath, can be described in terms of positive permittivity, while the complex plasma above has a negative permittivity. A peak corresponding to a maximum of the displacement is not always evident, see fig 2. It is clear when the crystal is deep in the sheath and the geometry is, as in fig1, almost a hemisphere. The radii are all equal and the resonance is narrow. The peak is smeared when the crystal

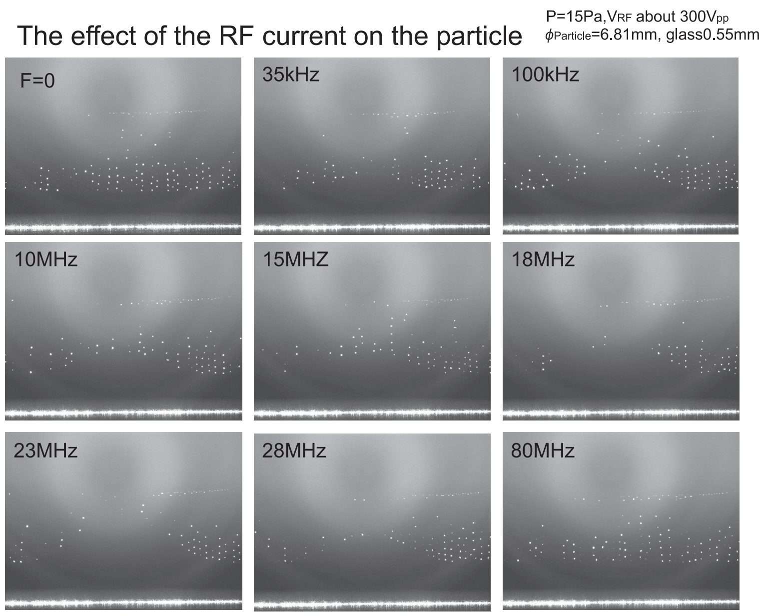

Figure 1: the displacement of the particles with frequency

levitates high in the sheath, near the plasma edge. In this case the current spreads in many possible paths, each with a different resonant frequency. In general the geometry is an hybrid, however we found a substantial coherence between the maximum, $f_{res.}$, and the cut-off, f_{pe}, as for planar geometry, [2]: $f_{res.} = f_{pe}\sqrt{2s/2s+p}$ with s the thickness of the sheath below the crystal and p, the path of the current in the crystal, equal to the small electrode dimension. The electron density in the crystal has been obtained from the definition of electron plasma frequency f_{pe}, a cut off unique to all the geometry, using the frequency of the last experimental point, at which the displacement of the particles is comparable with one particles' layer thickness. It is clear that only the free electrons participate to the resonances in the high frequency range. In plasma physics the presence of ions does not modify the electron plasma frequency, although the opposite is not true. In complex plasma, the lighter specie, electrons, has the same resonance as with no dust; we just mention here the propagation of Langmuir waves in dusty plasma. Some very small particles, on the top of the crystal, visible in fig. 1, do not shift their position at all, showing that the RF current does not reach there. For frequency above the cut-off, $>\simeq 100MHz$, the RF current approaches the plasma sheath resonance of the main two component plasma above the crystal and the resonant path closes to ground through the opposite electrode. In this case the assembly of particle is liquid, due to a 'shortage' of electrons, no longer in equilibrium, and the main plasma becomes brighter showing power deposition.

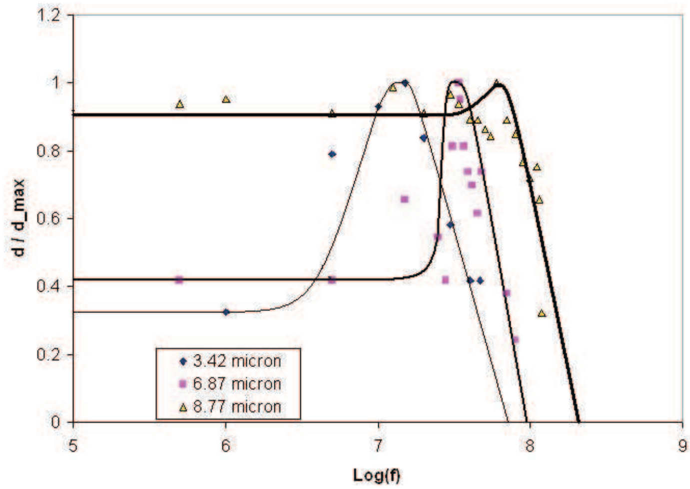

Figure 2: the displacement of the particles versus frequency

The RF sheath and derivation of the ion density- In the plasma sheath the electron density, n_e, has a Maxwellian distribution enhanced by the presence of RF [2]:

$$n_e = n_e(0)exp(\frac{eV_{DC}}{kT_e})I_0(\frac{eV_{RF}}{kT_e})\} \tag{1}$$

where V_{DC} and V_{RF} are the potentials in the sheath, both measured from the plasma (they have a constant ratio as measured by Langmuir probe), T_e is the electron temperature and I_0 is the zeroth order modified Bessel function of the first kind.

Usually ions are treated as collisionless in Argon sheaths up to 7Pa. Collisional calculations, based on the theory of Riemann [4] are not too different from collisionless calculations in our particular application because we are concerned only with the upper part of the sheath, about a third of the full sheath. Here we present a derivation of the ion density based on the collisionless hypothesis, this may lead to an under-esteem of the density of the ions of about 40per cent. Inserting n_e provided by the plasma sheath resonance in eq.2 we can derive the potential difference between the main plasma and the plasma crystal and the energy of the streaming ions. Consequently the ion density, n_i, is derived from the continuity eq.:

$$n_i = n_i(0)exp(-V_0)(1-V/V_0)^{-1/2} \qquad (2)$$

where $n_i(0) = n_e(0)$ and $V_0 = 1/2$ is the energy of the ions at the sheath edge. Note that we have not assumed any spatial distribution for the potential.

Characterization of the plasma crystal - The physical quantities measured, or derived, so far allow us to characterize the plasma crystal. Let's assume for now that the crystal is quasi-neutral, we shall be able to prove this statement shortly. If this is the case $n_i/n_e = n_g z_g/n_e + 1$. with n_g and z_g respectively the density and the charge of the grains. With the experimental densities for the three component of the plasma z_g is derived. Charge and mass of the particles give us the minimum electric field $\mid E \mid$ required for levitation (E may exceeds this value if the ion drag is relevant, it may not be important in our case). The field so derived is comparable or smaller than kT_e/L with L the vertical dimension of the crystal. This latter quantity is the maximum field sustainable by a quasi-neutral plasma; in this way the above statement of quasi-neutrality is self-consistently validated, see also fig. 3. The field of the crystal is also much smaller than the electric field derived by the solution of the un-perturbed Poisson equation with the RF enhanced electron density at the same position, see fig. 4. Apparently the maximum dimension of the crystal (and the maximum

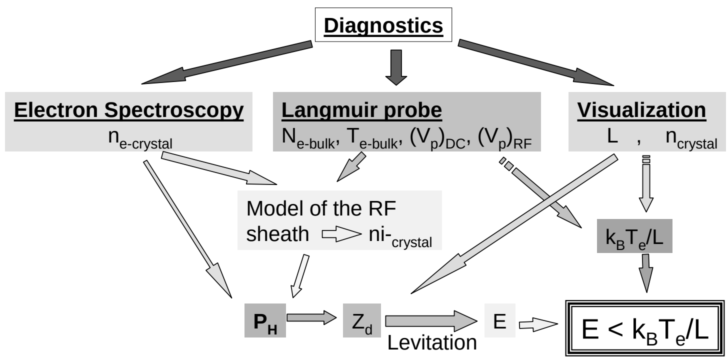

Figure 3: Flow chart of the data analysis

number of particle that can be levitated) is limited by the electric field required for levitation, at a given electron temperature.

Using the vacuum approximation, well proved for small particles, the floating potential of the grains, $V_{f-grain}$ has been derived. It is consistently lower, in absolute value, with respect to the floating potential predicted by the OML theory for isolated particles in a supersonic ion stream. Two counteracting effects may modify the charge on a grain in a crystal with respect to its charge when isolated. The neighboring grains limit the access of ions and this, in floating condition, would reduce the electron flow. The negative potential of the grain is consequently more repelling and higher in absolute value. However this effect is not applicable in our case because the Bohm flow out of the plasma, $\simeq 0.5A/m^2$ would sustain 10^5 layers. On the contrary, the space charge among grains is positive for interacting grains, possibly more positive than for the isolated grain at the same distance. In this case the ion flow would increase with respect to the isolated grain reducing the floating potential (in modulus) with respect to the isolated grain. This latter effect is in agreement with our data.

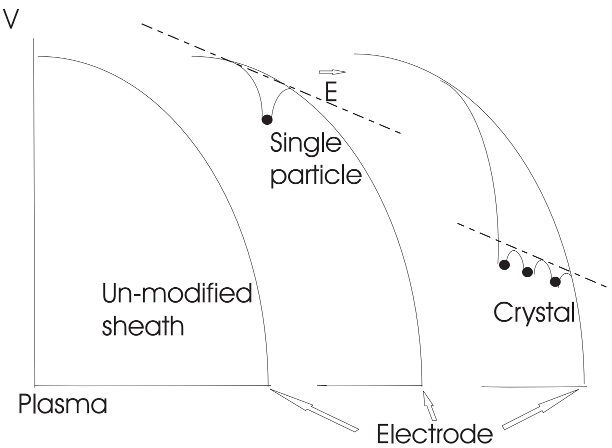

Figure 4: Schematic of the potential profile in the particle loaded sheath

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