Plasma Phys. Control. Fusion **46** (2004) B293–B299 PII: S0741-3335(04)86456-X

Pressure triggered collective oscillations of a dust crystal in a capacitive RF plasma

C M Ticoş[1], A Dyson[1], P W Smith[1] and P K Shukla[2]

[1] Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, UK
[2] Institut für Theoretische Physik IV, Fakultät für Physik und Astronomie, Bochum, D-44780 Bochum, Germany

Received 2 July 2004
Published 17 November 2004
Online at stacks.iop.org/PPCF/46/B293
doi:10.1088/0741-3335/46/12B/025

Abstract

Experimental results of vertical oscillations of dust grains in the driven electrode sheath of a capacitive RF plasma are presented. Below a certain pressure, waves suddenly start to propagate in the lower planes of a plasma crystal. Further decreasing the pressure causes the waves to spread in the entire dust cloud. The waves are found to propagate at constant frequency but with a higher phase velocity as the pressure is reduced. A mechanism based on the ion–dust two-stream instability is proposed to explain the observations. From the numerical solution the wave frequency is found to be highly dependent on the value chosen for the dust charge and so gives a diagnostic method for determining the charge on the dust.

1. Introduction

A collection of negatively charged micron size dust grains can be suspended in a plasma or plasma sheath as a result of a balance of an upward electrostatic force and the downward force of gravity and can form well organized structures called plasma crystals [1]. In an RF plasma the dust grains are suspended in the lower electrode sheath (usually the driven electrode) and acquire a large negative charge of typically 10^3–10^4 electrons [2].

The formation of dust crystals is attributed to an asymmetric interaction between the ions and the dust grains. Ions are accelerated to the electrode by the sheath electric field, and as they stream between the dust grains their trajectories are deviated and so form a spatially varying potential downstream of the dust grains called the wake potential [3]. This wake potential acts as an attractive potential well for the lower dust grains that tend to stack into columns below one another [4]. In the horizontal direction the negatively charged dust grains repel one another and a screened Coulomb potential accurately describes the dust–dust interaction [5].

Low frequency waves in a dust cloud are possible when the damping factors are low, due to the high inertia of the dust grains. Dust acoustic waves (DAWs) where dust grain oscillation is sustained by the electron and ion pressures were first predicted by Rao *et al* [6] in a multi-component plasma with negatively charged dust grains screened by the ions. Their existence was later confirmed in a dc nitrogen plasma at medium pressures (100 mTorr), where spontaneous wave patterns in the dust cloud travelled at a low speed, of about $\sim$12 cm s^{-1} [7], and in the diffuse edge of an inductive low pressure RF plasma [8]. The linear theory of DAWs applies to the case of weakly coupled dust grains in a plasma crystal. However, it has also been successful in approximating the dispersion relation obtained experimentally by exciting DAWs in a strongly coupled crystal [9].

The electrostatic interaction between the ions moving in the sheath and the relatively inert dust grains can lead to the development of various ion–dust stream instabilities [3, 10]. This type of instability is manifested by very low frequency dust waves and has been observed in laboratory experiments in the positive column of a dc plasma. Here the ions drift with small velocities, $u_{\rm i}$, due to the small electric field $E \sim 1\,{\rm V\,cm^{-1}}$, the drift being smaller than their mean thermal speed ($u_{\rm i} < v_{T_{\rm i}} = \sqrt{k_{\rm B}T_{\rm i}/m_{\rm i}}$, where $T_{\rm i} \approx 0.03$ eV) [11]. The typical frequency of these waves was $\omega \sim 60\,{\rm rad\,s^{-1}}$ with phase velocities $v_{\rm ph} \sim 1\,{\rm cm\,s^{-1}}$.

In this paper, we present experimental results of very low frequency self-excited dust waves, travelling in the direction of the streaming ions, in a dust crystal found in equilibrium in the sheath of an RF capacitive plasma. The wave excitation takes place during the phase transition of the dust cloud from a solid to fluid phase. As the pressure is lowered below a critical value, waves start to propagate suddenly in the lower planes of the crystal. Reducing the neutral drag on the dust grains by lowering the pressure further causes the waves to spread in the entire dust cloud and the grains to oscillate vertically with amplitudes greater than the separation between the horizontal layers of the initial crystal. The ions enter the sheath with the Bohm speed, $\sqrt{k_{\rm B}T_{\rm e}/m_{\rm i}}$, and are further accelerated by the sheath electric field. As a result the ion drift speed is very much greater than in the dc case, with $u_{\rm i} \gg v_{T_{\rm i}}$. The ion–dust two-stream instability is proposed to explain the wave excitation in the 'melted' crystal. Our experiments are in good agreement with the numerical results obtained by Joyce *et al* [12].

2. Theoretical considerations

A dust cloud found in a fluid-like state with weakly coupled dust grains is considered. The dispersion relation for the ion–dust two-stream instability can be written starting from the susceptibilities of each plasma component and making the appropriate approximations as [3, 10, 12]

$$0 = 1 + \frac{1}{k^2\lambda_{\rm De}^2} - \frac{\omega_{\rm d}^2}{\omega(\omega + {\rm i}\nu_{\rm d})} - \frac{\omega_{\rm i}^2}{(\omega - \boldsymbol{k}\cdot\boldsymbol{u}_{\rm i})(\omega - \boldsymbol{k}\cdot\boldsymbol{u}_{\rm i} + {\rm i}\nu_{\rm i})}, \qquad (1)$$

where $\lambda_{\rm De}$ is the Debye length, $\omega_{\rm i}$ and $\omega_{\rm d}$ are the ion and dust plasma frequencies, respectively, $\nu_{\rm i}$ and $\nu_{\rm d}$ are the collision frequencies of ions and dust grains, respectively, with the neutral gas, and $\boldsymbol{u}_{\rm i}$ is the ion streaming velocity. Of interest here are waves propagating along the direction of ion flow in the plasma sheath, i.e. $\boldsymbol{k}\boldsymbol{u}_{\rm i} = ku_{\rm i}$ with $\omega \ll ku_{\rm i}$. It has been assumed that $kv_{T_{\rm d}} \ll \omega$, $\nu_{\rm en} \ll kv_{T_{\rm e}}$, $u_{\rm i} \gg v_{T_{\rm i}}$, where $v_{\rm d}$, $v_{T_{\rm e}}$ and $v_{T_{\rm i}}$ are the thermal speeds of dust grains, electrons and ions, respectively. It is also assumed that ions enter the sheath with the Bohm speed. The ion–neutral collision frequency is taken as $\nu_{\rm i} \approx u_{\rm i}n_n\sigma_{\rm in}$, with the collisional cross-section $\sigma_{\rm in} = 3\times10^{-15}\,{\rm cm^{-2}}$ [10]. At a pressure of 0.2 Torr the ion mean free path is $\approx$0.5 mm, comparable with the wavelength of the observed oscillations. The neutral drag force on a dust grain with radius r is calculated using the Epstein expression [13]. The dust–neutral

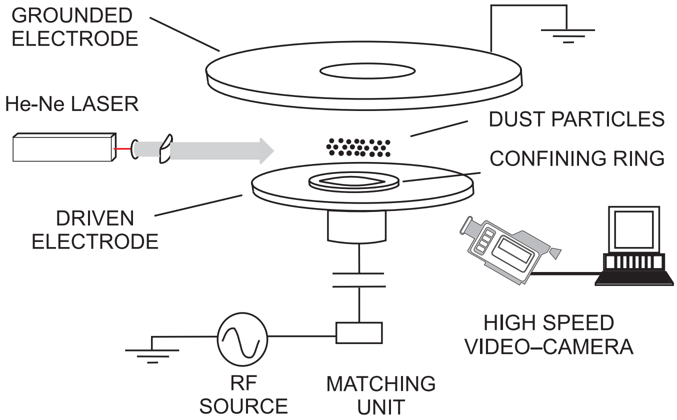

Figure 1. Experimental set-up.

collision rate is therefore given by

$$\nu_{\mathrm{dn}} = \frac{4}{3}\sqrt{\pi} r^2 \frac{P}{m_{\mathrm{d}} v_{\mathrm{th}}} \left(1 + \frac{\pi}{8}\right), \tag{2}$$

where m_{d} is the dust mass, v_{th} is the neutral gas thermal velocity and $P = n_{\mathrm{n}} k_{\mathrm{B}} T_{\mathrm{n}}$ is the pressure of the neutral gas.

The solutions, $\omega(k)$, of equation (1) can be found numerically for our experimental parameters. By taking $\omega = \omega_{\mathrm{r}} + \mathrm{i}\gamma$, ω_{r} corresponds to the observed frequency of the waves, while $\gamma > 0$ indicates the development of an instability.

3. Description of the apparatus and diagnostic method

The results are obtained in a capacitively coupled RF discharge rig with plane horizontal electrodes (figure 1). Dust grains are introduced through a hole in the upper grounded electrode and fall through the plasma before forming horizontal layers in the sheath of the lower driven electrode. The metal chamber walls are also grounded, so giving an asymmetric plasma with most of the dc self-bias voltage drop across the driven plate sheath. A copper ring with an inner diameter of 37 mm and a height of 2 mm slightly curves the sheath edges and serves to confine the dust. The gas pressure is measured by a Capacitron Leybold gauge with a relative error of 10^{-2} in the working range of 10–500 mTorr. Stable dust crystals are easily obtained above 200 mTorr at peak-to-peak (p–p) RF voltages of about 100–140 V.

The dust grains are spherical and made of melamine formaldehyde (MF), with a diameter $d = 3.4\,\mu$m. They are dropped from a dust container situated above the top electrode. They are illuminated with a narrow vertical sheath of light with variable width produced by passing a He–Ne laser beam through a cylindrical lens. By changing the position of the lens it is possible to select one or several vertical crystal planes.

The dust waves are recorded by a high speed digital video-camera with a resolution of 496×358 pixels and an 8-bit greyscale depth. The focal length of the camera objective is set for a clear view of the central part of the dust crystal. A correspondence of 57 pixels per millimetre is determined using a millimetre ruler placed at the same position as the crystal layers. The video-camera has the capability of acquiring several thousand frames at a rate of 250 frames per second. The images are then processed with dedicated codes, developed in house. The dust grains appear as bright spots against a dark background with a size of a few pixels. A number between 1 and 256 is attributed for each pixel in the image, according to its brightness. A good contrast ratio of about 5 : 1 is achieved for the regions where dust is present. A designated rectangular area of about 200×110 pixels situated in the centre of the acquired frames is used to track the waves. This rectangle is divided into 110 rows, and the dust density on a row is taken as the sum of all the pixel values along that row. The wavefronts of the DAWs are characterized by a local agglomeration of grains, resulting in a higher brightness on specific rows. Thus a plot of the row intensity versus the row index shows a peak at the position of each wavefront. The phase velocity of the waves is deduced by monitoring the exact position of the peak at successive moments of time. The frequency of the waves is inferred from the time it takes for the peak to cross a designated position in the dust cloud. The wave vector is then calculated as $k = \omega/v_{\rm ph}$. For better accuracy, the procedure is repeated and the values averaged over more than 100 wave cycles.

The plasma parameters are deduced with an active Langmuir probe, introduced midway between the electrodes, separated by 4 cm [14]. The probe is actively compensated with RF applied to the probe tip using a three-harmonics box and a low power (50 W) RF amplifier. The three-harmonics box samples the RF waveform at the driven electrode and uses phase locked loops to generate signals at the fundamental, second and third harmonics. The amplitude and phase of each harmonic is adjusted until the RF voltage drop across the probe sheath is effectively removed so that dc probe theory can be used. A digitized acquisition system averages over many I–V characteristics and provides the values for electron temperature $T_{\rm e} \approx 3.2$–3.5 eV and concentration $n_{\rm e} \approx 1.5$–1.8×10^9 cm^{-3}, and plasma potential $V_{\rm p} \approx 32$ V.

4. Results and discussion

A dust crystal is possible when the mutual forces of interaction are reciprocally balanced, and the potential energy of the dust cloud reaches a minimum. The frictional force with the neutral gas has an important contribution to the stability of the crystal. At medium pressures ($>$200 mTorr), the drag exerted by the neutrals quickly dissipates the kinetic energy of grains, and the dust cloud 'condenses' into a steady, solid-like state. At low pressures, however, any small deviations from equilibrium remain undamped and can grow in time and the dust crystal 'melts' into a fluid-like state [15]. The neutral gas pressure can be regarded as an 'order' parameter that controls the state of the dust cloud [12].

A side view of the crystal at an argon pressure $P = 0.198$ Torr and $V_{\rm RF}^{\rm (p\text{–}p)} = 140$ V is presented in figure 2(*a*). The distance between grains measured on several pictures of the stable crystal is found to be $\Delta d_{\rm p} = 0.16$ mm. This gives the number density of grains as $n_{\rm d} \approx 2.5 \times 10^5$ cm^{-3}.

At a critical gas pressure $P_{\rm C} = 0.188$ Torr an instability suddenly occurs in the lower layers of the crystal, producing waves travelling downstream with the ion flow. The wavefront is formed in the middle crystal and propagates to the bottom of it as a dust wave, due to the collective motion of grains around their equilibrium position. The amplitudes of the grain motion are less than the layer separation, so that the initial crystal-like structure is preserved. The measured phase velocity is $v_{\rm ph} = 1.96$ cm s^{-1}, while the propagation distance is $L_{\rm wave} \approx 0.9$ mm. As the neutral gas pressure is slowly decreased at a constant RF voltage, it is observed that both the phase velocity of the waves and the propagation distance increase, while the frequency of the waves remains constant at about $\omega_{\rm exp} \approx 182$ rad s^{-1}. The dependence of the phase velocity, $v_{\rm ph}$, and the wave vector $k = \omega/v_{\rm ph}$ on the gas pressure is shown in figure 3. The wave vector decreases towards lower pressures. Measurements are taken at 5 mTorr intervals below the critical pressure. The change of only a few per cent in the gas

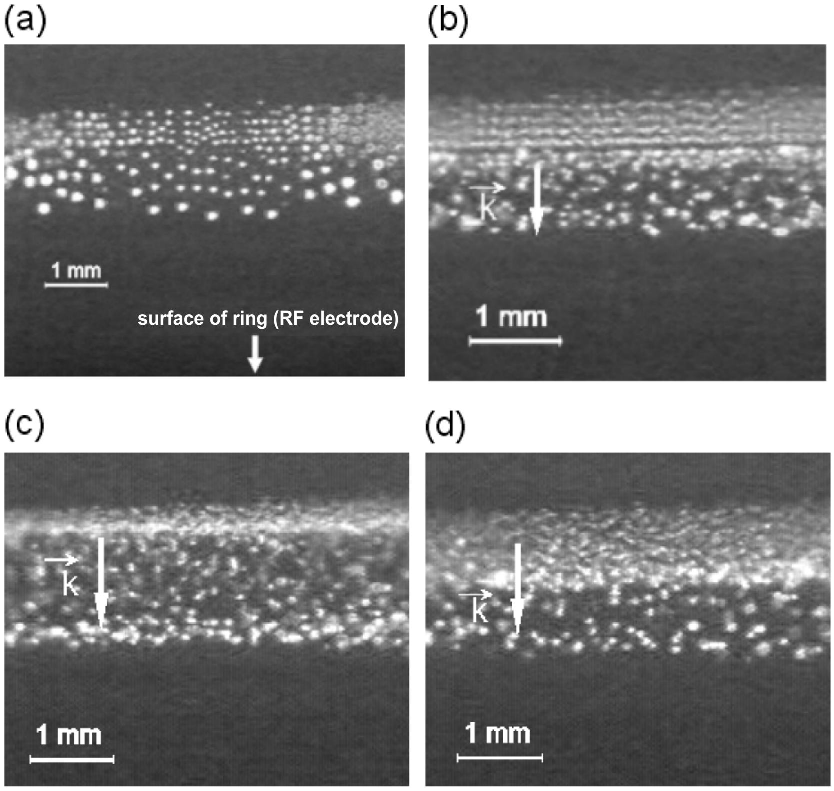

Figure 2. Onset of the instability: (*a*) side view of one vertical crystal layer at $P = 0.198$ Torr; (*b*) waves propagate only in the lower crystal planes at $P = 0.185$ Torr (the critical pressure is $P_C = 0.188$ Torr); (*c*) and (*d*) wavefront propagating at $P = 0.160$ Torr in frames separated in time by 16 ms.

pressure over the measurement range is small enough to not affect the plasma parameters and the vertical length of the crystal. However, the position where the wavefront is first formed moves towards the upper part of the crystal. It is worth mentioning that in these present observations, only one wavefront at a time is seen, possibly due to the short vertical length of the crystal. As the wavefront reaches the lower part of the crystal a new one is formed in the upper crystal layers. At $P = 0.160$ Torr the waves are formed at the top of the dust cloud and propagate with $v_{ph} = 3.8\,\mathrm{cm\,s^{-1}}$ over its whole vertical extent $L_{wave} \approx 1.7$ mm. The amplitudes of the grains are now much larger than the initial crystal layer separation, and the ordered crystal structure is lost. The kinetic energy of grains increases continuously as the pressure is reduced. Below 0.08 Torr their oscillating trajectories become random. The wave-like motion disappears and the dust cloud reaches a fluid-like state.

A two-stream ion–dust instability is suggested to be the mechanism for the self-excitation of the observed waves. The most unstable mode is studied by solving numerically the dispersion relation given in equation (1). The curves for $\omega_r(k)$ and $\gamma(k)$ are shown in figure 4. The following parameters are used: $T_e = 3.5$ eV, $n_e = 2 \times 10^9\,\mathrm{cm^{-3}}$, $u_i = \sqrt{k_B T_e/m_i} = 2.9 \times 10^3\,\mathrm{m\,s^{-1}}$ and $Z_d = -2 \times 10^3$ e. This charge value is chosen so that for the most unstable mode the wave frequency agrees with experiment. The solution depends on the neutral pressure via the collisional terms ν_i and ν_d. It is found numerically that the critical pressure for the onset

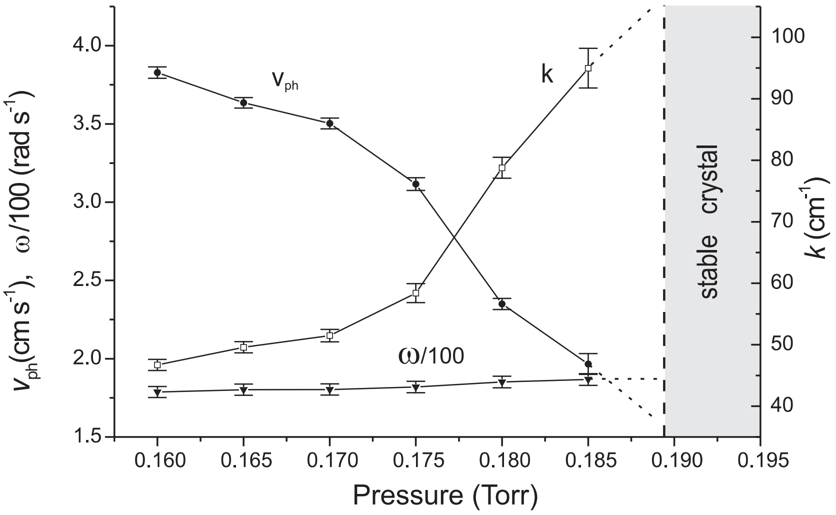

Figure 3. Dependence of the measured phase velocity, v_{ph}, and frequency, ω, on the neutral gas pressure, below the critical pressure $P_C = 0.188$ Torr. The wave number is calculated as $k = \omega/v_{ph}$.

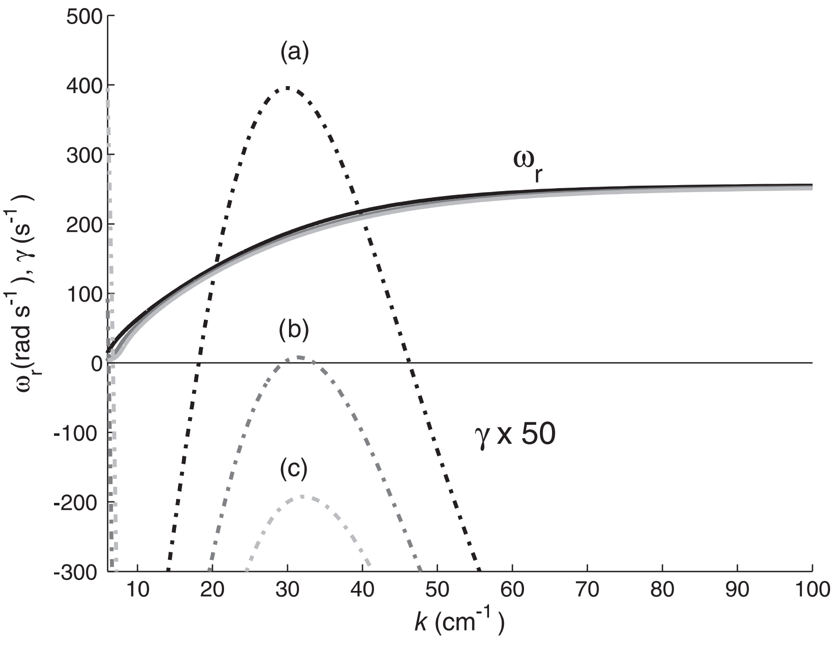

Figure 4. Growth rate, γ, and wave frequency, ω_r, versus wave number, k, for different fill pressures: (a) for $P = 0.3$ Torr, $\gamma < 0$ for all k; (b) for $P = 0.275$ Torr, $\gamma \approx 0$ for $k = 30\,\text{cm}^{-1}$ (here $P = P_C$) and (c) for $P = 0.23$ Torr, $\gamma > 0$ over a wider k range.

of the instability (i.e. when $\gamma > 0$) is $P_C \approx 0.275$ Torr for $n_d = 2 \times 10^5\,\text{cm}^{-3}$. The model gives good qualitative agreement with the experimental observations, in spite of its simplicity, which does not account for the dust–dust correlations nor the variation of grain charge with position.

5. Conclusions

The self-excitation and propagation of DAWs in the direction of ion flow in the plasma sheath is observed in a dust cloud when the neutral gas pressure is lowered below a certain threshold. The frequency of the waves is roughly constant and independent of pressure, while the phase velocity increases as the pressure is reduced. The two-stream ion–dust instability is thought to be the mechanism of wave formation. A dispersion relation, deduced from the susceptibilities of each plasma component and taking into account the collisions of ions and dust grains with the neutral gas, is studied. The numerical solutions of this equation predict a positive grow rate of the instability below a critical pressure.

Acknowledgments

The authors wish to thank EPSRC for the loan of the high speed digital video-camera (NAC-500). This research was partially supported by the European Commission (Brussels) for carrying out the task of the RTN 'Complex Plasmas' through contract No HPRN-CT-2000-00140.

References

[1] Thomas H *et al* 1994 *Phys. Rev. Lett.* **73** 652
Chu J H and Lin I 1994 *Phys. Rev. Lett.* **72** 4009
[2] Ticos C M, Dyson A and Smith P W 2004 *Plasma Sources Sci. Technol.* **13** 395
[3] Shukla P K and Mamun A A 2002 *Introduction to Dusty Plasma Physics* (Bristol: Institute of Physics)
[4] Takahashi K *et al* 1998 *Phys. Rev.* E **58** 7805
Hebner G A *et al* 2003 *Phys. Rev.* E **68** 016403
Ticos C M, Smith P W and Shukla P K 2003 *Phys. Lett.* A **319** 504
Ticos C M, Smith P W and Shukla P K 2004 *Phys. Scr.* T **107** 117
[5] Liu B, Avinash K and Goree J 2004 *Phys. Rev.* E **69** 036410
Konopka U, Morfill G E and Ratke L 2000 *Phys. Rev. Lett.* **84** 891
[6] Rao N N, Shukla P K and Yu M Y 1990 *Planet Space Sci.* **38** 543
[7] Barkan A, Merlino R L and D'Angelo N 1995 *Phys. Plasmas* **2** 3563
Thompson C, Barkan A, Merlino R L and D'Angelo N 1999 *IEEE Trans. Plasma Sci.* **27** 146
[8] Fortov V E, Usachev A D, Zobnin A V, Molotkov V I and Petrov O F 2003 *Phys. Plasmas* **10** 1199
[9] Pieper J B and Goree J 1996 *Phys. Rev. Lett.* **77** 3137
[10] Rosenberg M 2002 *J. Plasma Phys.* **67** 235
Rosenberg M 1996 *J. Vac. Sci. Technol.* A **14** 631
[11] Fortov V E, Khrapak A G, Khrapak S A, Molotkov V I, Nefedov A P, Petrov O F and Torchinsky V M 2000 *Phys. Plasmas* **7** 1374
[12] Joyce G, Lampe M and Ganguli G 2002 *Phys. Rev. Lett.* **88** 095006–1
[13] Epstein P S 1924 *Phys. Rev.* **23** 710
[14] Dyson A, Bryant P and Allen J E 2000 *Meas. Sci. Technol.* **11** 554
[15] Thomas H M and Morfill G E 1996 *J. Vac. Sci. Technol.* A **14** 501