

2003

Laboratory-device configurations for investigating new dusty-plasma equilibria

M E. Kopke
West Virginia University

N Sato
West Virginia University

Follow this and additional works at: https://researchrepository.wvu.edu/faculty_publications

Digital Commons Citation

Kopke, M E. and Sato, N, "Laboratory-device configurations for investigating new dusty-plasma equilibria" (2003). *Faculty & Staff Scholarship*. 2883.
https://researchrepository.wvu.edu/faculty_publications/2883

This Article is brought to you for free and open access by The Research Repository @ WVU. It has been accepted for inclusion in Faculty & Staff Scholarship by an authorized administrator of The Research Repository @ WVU. For more information, please contact ian.harmon@mail.wvu.edu.



Laboratory-device configurations for investigating new dusty-plasma equilibria

To cite this article: M E Koepke and N Sato 2003 *New J. Phys.* **5** 42

View the [article online](#) for updates and enhancements.

Related content

- [Studies of ion-acoustic and ion-cyclotron waves](#)
M E Koepke, C Teodorescu and E W Reynolds
- [Review article](#)
A Piel and A Melzer
- [Dusty plasmas](#)
Vladimir E Fortov, Aleksei G Khrapak, Sergei A Khrapak et al.

Recent citations

- [Simulation and experiment of X-ray communication in re-entry dusty plasma region](#)
Yao Li *et al*
- [Ion-Flow-Induced Excitation of Electrostatic Cyclotron Mode in Magnetized Dusty Plasma](#)
P. Bezbaruah and N. Das
- [Wake potential in 2-D magnetized complex plasma](#)
Pratikshya Bezbaruah and Nilakshi Das

Laboratory-device configurations for investigating new dusty-plasma equilibria

M E Koepke and N Sato¹

Physics Department, West Virginia University, Morgantown, WV 26506-6315, USA

E-mail: mkoepke@wvu.edu

New Journal of Physics **5** (2003) 42.1–42.14 (<http://www.njp.org/>)

Received 10 December 2002

Published 9 May 2003

Abstract. Two configurations that are designed for laboratory investigations of dusty-plasma equilibria are being prepared for operation. The first configuration has a vertical magnetic field that confines horizontally a vertically oriented, 6.4 cm diameter, low-temperature, alkali-metal-ion plasma column. The plasma is produced via the Q-machine method (Rynn and D'Angelo 1960 *Rev. Sci. Instrum.* **31** 1326) with contact-ionized alkali-metal ions and thermionically emitted electrons. The dust grains will be injected to form a small number of horizontal dusty-plasma layers levitated electrostatically above the plasma sheath. The advantage of using a Q-machine plasma source is the insensitivity of its plasma production to the background pressure of neutral particles. The plan is to study the competition between neutral-particle cooling and streaming-ion energization in dusty-plasma crystallization and decrystallization (i.e., freezing and melting) over a wide range of neutral-particle pressure. The second configuration has a large vacuum chamber (2 m diameter, 4 m length) and a large, solenoidal, magnetic field (0.1 T) that will magnetically confine small-diameter dust grains in a large-volume dusty plasma. The advantage of producing a large-volume, dusty plasma in a strong magnetic field is the ability to meet the criterion that the dust gyroradius is much smaller than the dusty-plasma-column diameter. The plan is to study third-component effects in microinstabilities and the influence of size distribution on magnetized dusty-plasma equilibrium and stability.

¹ Permanent address: Tohoku University, Sendai 980-8579, Japan.

Contents

1. Introduction	2
2. A vertical Q-machine configuration for investigating phase-transition physics in plasma crystals	3
3. Neutral-particle cooling of dust grains versus streaming-ion energization of dust grains	4
4. Magnetized dusty plasma	7
5. Instabilities in magnetized dusty plasma	10
6. Conclusions	11
Acknowledgments	11
References	11

1. Introduction

Plasma, i.e., free electrons and ions (typically charged singly and positively) that behave classically and collectively via the long-range electromagnetic force, meet the criteria that the Debye-shielding scale length is both much larger than the interparticle spacing and much smaller than the plasma dimensions. Plasma is considered dusty if it contains relatively massive particulates (e.g., dust grains) with net charge. The dusty plasma is considered magnetized if the charge-to-mass ratio of the dust grain is sufficiently large that a significant fraction of the grains have gyroradii much smaller than the dusty plasma's dimensions perpendicular to the magnetic field. Note that the word 'magnetized' does not refer to the appearance of north and south magnetic poles on an individual stationary dust grain. However, the gyromotion of a charged dust grain produces a magnetic dipole and this dust magnetization is diamagnetic, as is the magnetization of plasma electrons and ions. Of the two devices described in this paper, one is designed to produce large-volume magnetized dusty plasma.

Various laboratory devices have been utilized to investigate the properties of dusty plasmas. Early work was performed in discharge-tube plasmas [2], Q machines [3]–[5], plasma-processing devices [6], filament-source plasma devices [7]–[10] and rf-source plasma devices [11]–[15]. In some of these devices, the lifetime of an individual dust grain in the dusty plasma is the free-fall plasma-transit time, too small for the dynamics or transport of the dust population to be influenced by collective effects such as waves and instabilities. In the other devices, a vertical electric force qE exists that opposes the gravitational force mg , allowing the possibility of significantly increasing the dust-grain lifetime by levitation. The additional horizontal component of the electric field that exists in some configurations affords horizontal confinement to a typically circular region that can result in indefinitely long dust-grain confinement. Magnetic confinement, possible when the dusty plasma is magnetized as described above, not only increases dust-grain lifetimes but introduces a unique dynamical role for the charge-to-mass ratio q/m .

The dust-grain kinetic energy, the ratio q/m of the dust-grain population and other dust parameters are affected by the kinetic energy of the electron and ion populations and the density of background neutral gas. The interdependence of charged-particle kinetic energy and neutral-particle pressure that is typical in discharge-tube, rf-source and filament-source plasmas complicates attempts to independently investigate the effects of plasma and neutral-gas properties on the Coulomb coupling parameter $\Gamma \equiv q^2(4\pi\epsilon_0 dk_B T_d)^{-1} \exp(-d/\lambda_D)$, where d is

the intergrain spacing, k_B is Boltzmann's constant, T_d is the kinetic temperature of the dust-grain population and λ_D is the Debye length. For Γ values above 170, the coupling of the dusty plasma is sufficiently strong that a Coulomb solid forms [16, 17]. Since neutral gas is responsible for viscous drag forces on the dust grain, increasing the background neutral-gas pressure decreases the value of T_d , and so, a common method for incrementing Γ involves the adjustment the neutral-gas density, even though the adjustment typically alters other plasma and dust-grain properties. In Q machines, unlike some other plasma devices, the plasma is generated without the need of neutral gas, causing the plasma kinetic energies to be relatively insensitive to adjustments in the neutral density. Thus, adjustments to T_d can be made by changing the background neutral-gas pressure without the accompanying changes in electron and ion temperatures, plasma density and dust-grain charge state that are encountered in the other plasma devices. The second of two devices described in this paper is designed to produce electrostatically confined, strongly coupled, dusty plasma with relatively independent control of q , λ_D and T_d .

2. A vertical Q-machine configuration for investigating phase-transition physics in plasma crystals

The average kinetic energy of dust grains in dusty plasma is sensitive to the viscous forces exerted by neutral particles. Whereas the dust grains are relatively quiescent at elevated neutral pressure, their random motion becomes violent at low pressure. Directly related to this transition in kinetic temperature is a transition, which occurs at a critical value of neutral pressure, between the dust-crystal phase and a dust-fluid phase [18, 19]. This critical value of neutral pressure depends on the interplay between viscous drag caused by dust-neutral collisionality and the dust energization resulting from ion-relative-to-dust streaming instabilities [20]–[25]. Isolating either of these two processes is difficult in discharge plasmas, for which even a half-order-of-magnitude change in neutral pressure sensitively affects the collisional ionization responsible for producing the plasma. In contrast, because Q-machine plasma production is independent of collisions, neutral pressure can be varied over four orders of magnitude without significantly affecting the Q-machine plasma properties [26]–[28], making the device well suited for investigating the separate roles of viscous drag and streaming instabilities in dusty plasma.

The threshold streaming speed for streaming instabilities is comparable to the value of the ion sound speed which, in a Q-machine plasma for which $T_e/T_i \approx 1$, is comparable to the ion thermal speed and thus within easy reach experimentally. In rf-source plasma or discharge-tube plasma, for which $T_e/T_i \approx 40$, the ion sound speed is much larger than the ion thermal speed, making the threshold less accessible except in the direction perpendicular to the sheath plane for which supersonic, sheath-crossing ion drifts are common. In the direction perpendicular to the sheath plane, sheath-crossing drift speeds of the charged particles can be adjusted to be smaller than or larger than the ion thermal speed by operating the Q-machine source in either the ion-rich or electron-rich regime [29]. Producing and controlling ion drifts in a plane parallel to the sheath from zero to several times the ion thermal speed is possible by contouring the radial profile of plasma potential, for example using biased end-electrode segments [30, 31]. Thus an advantage of using a Q machine is the ability of examining cases of sheath-plane and sheath-crossing ion flow well into either the subsonic or supersonic regimes.

To levitate a single layer of dust grains in dusty plasma, the gravitational force is balanced by an electric force generated by a horizontal, negatively biased plate. This plate can be either a nonemitting conducting boundary of the plasma or the emitting electrode on which the plasma-

producing contact ionization and thermionic emission occurs. A Q-machine plasma column is bounded by such plates, but the plates are typically not horizontal. If the magnetic field is normal to the plane of the plate's sheath, an applied $E \times B$ drift makes a convenient means for introducing ion-relative-to-dust flow in the plane of the levitated dust layer. For one of these plates to simultaneously levitate the dust layer and produce $E \times B$ flow, the plasma column and magnetic field of the Q machine must be oriented vertically so that the plate is horizontal. Q machines used for conventional, dusty and fullerene (C_{60}^-) plasma research are designed to be long to generate plasma waves with wavevectors covering wide ranges in magnitude and angle, and thus are horizontal with biased plates in a vertical plane. Although orienting a Q machine vertically is atypical, this is the correct orientation for indefinitely confining a dusty-plasma layer.

3. Neutral-particle cooling of dust grains versus streaming-ion energization of dust grains

The primary issue to be addressed with the vertical Q machine is the independent evaluation of neutral-particle cooling and streaming-ion energization in dusty-plasma phase changes. The streaming of ions past stationary dust grains can dramatically affect the stability properties of the dusty plasma equilibrium. Examples of instabilities driven by ions streaming relative to dust include two-stream instabilities [32, 33] and the dust-acoustic instability [34, 35]. Recently, streaming instabilities that are driven unstable by the dissipative effects of dust charging have been shown [24] to be distinctly different from the dust-acoustic instability. Such streaming instabilities lead to the dust energization that prevents the formation of a crystal lattice in dusty plasmas [25].

The vertical Q-machine configuration can be used to investigate the competition between the dust-energizing effect of ion-relative-to-dust streaming instabilities and the dust-cooling effect of viscous drag forces caused by dust-neutral collisions over a wide range of neutral pressure and ion-streaming speed. These processes compete before, during and after a phase transition in establishing the dust kinetic temperature. The sheath-accelerated (directed), $E \times B$ (directed), and thermal (random) streaming of ions can be monitored using laser-induced fluorescence [36]. Dust kinetic energy can be monitored by video imaging of laser light scattered from individual dust grains [17]. As the value of neutral pressure is incremented from one extreme to the other, each new value of ion streaming associated with the phase transition can be measured and the transition hysteresis determined.

The growth rate of ion-relative-to-dust streaming instabilities maximizes at subsonic streaming speeds [37], motivating us to investigate the range of ion streaming from much less than to much more than the ion sound speed. By combining adjustments to the potential of plasma-column end boundaries and relative fluxes of ions and electrons from the plasma sources, we have already achieved this range of ion streaming in the WVU Q machine for the case of conventional plasma [38]. In all cases, we generate the plasma sheath. In the vertically oriented plasma column of the vertical Q machine, this sheath's electric field can levitate the dust grains. In the vertical Q machine, upward, downward and horizontal (i.e., in the sheath plane) ion streaming can be investigated. For example, having the ions supplied from the top plasma source and accelerated downward in the bottom source's sheath can produce large values of ion streaming speed in the vicinity of the dust layer, whereas having the ions supplied from the bottom plasma source will produce vertical migration at a small fraction of the ion thermal speed. Horizontal (azimuthal) ion flow up to two or three times the ion thermal speed can be induced by radial electric fields [31] that result in $E \times B$ streaming of the ions relative to the dust grains.

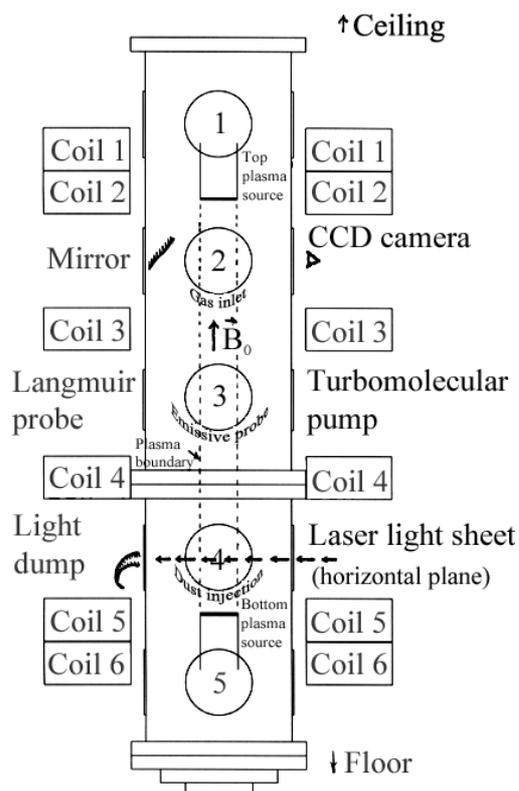


Figure 1. Configuration (side view) of the vertical Q machine. Rectangular cross sections of the six magnets surround the chamber. Q-machine plasma sources are shown as three-sided rectangles just below port no 1 and just above port no 5. Each port number designates four ports (front, back, right and left). Attachments on three of the four are labelled; the other is a viewport. The dust layer gets illuminated by laser light entering through the viewport at port no 4. The CCD camera at port no 2 uses a tilted mirror to image the horizontal dusty-plasma layer.

The vertical Q machine has a Q-machine source at the top and/or bottom of a vertically oriented cylindrical vacuum chamber immersed in a vertically oriented dc magnetic field, as shown in figures 1 and 2. A non-emitting termination electrode can replace either source. This general configuration can produce electrostatically trapped, dusty plasma in which the neutral gas pressure can be adjusted from 10^{-5} to 10^{-1} Torr and the dusty-plasma phase can be adjusted from gaseous, to fluid, to crystal. Since the effects of the gas pressure on the plasma dynamics can be considered slight and the effects on the dust dynamics are dramatic, we have the capability to independently adjust the viscous drag caused by dust–neutral collisionality and the dust energization caused by ion streaming. The upper operational limit on neutral pressure is determined by the ability of the plasma source to sustain contact ionization (which has been studied) and the negative effects on the dusty plasma of gas convective instabilities, smaller mean free paths and axial degradation of the plasma column (which has not been studied). We control the magnitude and direction of ion streaming using parallel and perpendicular (to the magnetic field) electric fields that are produced with biased segmented disc electrodes [30]. We plan to induce spin about the dust-grain axis using the opposing viscous forces of neighbouring counter-



Figure 2. Photograph of the vertical Q machine during construction, with graduate student Eric Reynolds. Some probes are attached to the chamber. Magnet power, cooling water and plasma sources are not yet installed.

streaming ion-stream layers on large dust grains [39, 40]. This counter-streaming is generated using multiple, concentric, differently biased, electrode segments [31]. Such spinning, charged, dust grains will have a magnetic moment. A crystal lattice of macroscopic magnetic dipoles, a variation of the recently discovered Coulomb solid, would resemble in some ways more-common solid magnetic material. On the international space station, where the gravitational forces are much smaller than on Earth, such a new material could be created with even larger dust grains. With these larger grains, the magnetic moment can be much larger. The understanding of the complicated interaction between moving point charges and macroscopic charge distributions is of interest not only in the field of dusty plasmas, but also in the field of general electromagnetic theory and in the field of gravitation [41].

A secondary issue that can be addressed in the vertical Q-machine configuration is the interaction between a passing or orbiting point charge and a charged, spherical dust grain, which is much more complicated than previously believed [41]. The torques exerted by streaming and orbiting charges on the grain are only the initial stages of a complex and unknown sequence of events. This sequence is quite different from the attraction–repulsion interaction usually associated with a point charge moving past a stationary charge. In the orbiting case, the dust grain continuously accelerates and the stability of the system has not been predicted. Since the sum of mechanical angular momentum and electromagnetic angular momentum must be constant, a precise balance between magnetic and electric fields of the point and grain charges should be observed.

The possibility of inducing spin in large micron-size dust grains using counter-streaming layers of ion flow that exert on each dust grain both viscous-related torque and Coulomb-related torque suggests that magnetic-dipole interactions between neighbour dust grains, in addition to the electrostatic interactions, can affect the phase transition in a dust crystal. The vertical Q-machine configuration is expected to enable such spinning to be induced.

4. Magnetized dusty plasma

In the laboratory, the usual experimental devices used to investigate dusty plasmas are not designed to meet the magnetized-dusty-plasma criterion. Exceptions, in which cases it may be possible that small dust grains could be magnetized, are two Tohoku University devices in Sendai, Japan, one of which is small (<0.1 m diameter) and was intended for investigating small dust clouds at sub-kiloGauss field strengths [42] and the other of which was used for investigating the rotation of fine-particle clouds at field strengths up to 40 kG [40], and a Max Planck Institute device in Garching, Germany, which is small (<0.5 m diameter) and intended for investigating plasma crystals [43] at field strengths up to 5 T [44].

Factors important in magnetizing a dust grain, besides the magnetic field strength, are the charge-to-mass ratio of the dust grain, the component of the dust grain speed perpendicular to the magnetic field (i.e., the dust kinetic temperature) and the dimensions of the dusty-plasma column. The charge depends on the dust grain's capacitance (i.e., on size and shape) and on the dust grain's electrostatic potential (i.e., the 'floating' potential) relative to the plasma's electrostatic potential. The mass depends on the dust grain's volume (i.e., on size and shape) and on the dust grain's mass density. In general, a population of dust grains would have a distribution of values of charge-to-mass ratio. The speeds associated with a population of dust grains would also be distributed, in general. Such a distribution of speeds is often modelled as Maxwellian, assigned a 'kinetic' temperature and represented by the root-mean-square value, referred to as the thermal speed. The temperature of the dust-grain material is typically room temperature and negligibly influences the equilibrium and dynamics of the dusty plasma.

Let us consider the case of Barkan *et al* [45] as an example of an experiment involving unmagnetized dust grains. They report a value of $5 \mu\text{m}$ for the average grain diameter, 0.8 V for the grain surface potential, 0.4 T for the magnetic field and 2 g cm^{-3} for the value of grain mass density of the grain material. A value of dust thermal speed can be calculated from estimating 0.1 eV for the average kinetic energy of the grains, based on the lowest values in other experimental devices [46]. Using these values, the grain gyroradius is on the order of 1 m. Since they report 6 cm for the plasma-column diameter, the dust is far from being magnetized.

By using values associated with much smaller grain diameter ($0.005 \mu\text{m}$), much smaller dust mass density (0.5 g cm^{-3}), much smaller dust thermal speed (average kinetic energy of 0.03 eV) and much larger magnetic field (1 T), D'Angelo [47] arrives at a dust-grain gyroradius of 0.26 cm. From this, he concludes that, as unrealistic as his values are for the present, future technology may increase the chances of achieving his values, and therefore it may become possible eventually to magnetize dust in laboratory plasma. A different approach, described here, is applied to the problem of producing magnetized dusty plasma. The large (1.8 m diameter, 4 m length) vacuum vessel recently outfitted with equipment and instrumentation at West Virginia University is referred to as the Gold Tank. Four other reports of magnetic effects on charged dust in inhomogeneous magnetic fields are related to work planned on the Gold Tank. In the first experiment [48] the authors discuss $E \times B$ drifts of the dust grains, and in the second experiment [49, 50] the authors discuss dust-ring formation in the vicinity of a magnetic dipole, but in neither experiment was the dust magnetized. In the third report, Luo and D'Angelo [51] discussed the possibility that certain effects observed in a dusty-plasma device with a homogeneous magnetic field might be due to the magnetization of very small (1–5 nm) dust grains, but such particles were undetected. In the fourth experiment [40], the particles did not move in gyro-orbits but spun with an angular frequency that changed with adjustments in the

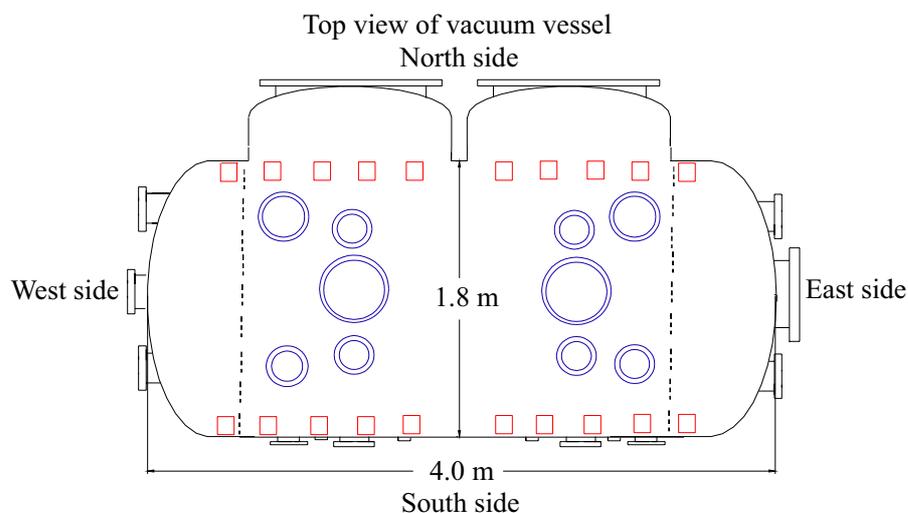


Figure 3. The experimental configuration (top view) in the Gold Tank. Note the ten diagnostic ports on the top of the chamber. The bottom of the chamber has an identical configuration of ports. Side ports are shown either flush with the chamber wall or on short extensions. The rectangular cross sections of the ten electromagnets are aligned along the inner wall of the chamber. Two large lobes on one side provide room for the electrical and cooling-water connections to the electromagnets. Electrical connections to the right- and left-hand plasma-source filament arrays (filament segments not shown; dashed segments represent mesh segments) are made through ports in the end flanges.

magnetic field. This experiment is also related to the spinning-dust-grain experiments planned for the vertical Q machine, described above.

Compared to Q-machine plasma, the Gold-Tank plasma will have a diameter 25 times larger, an electron temperature ten times larger and a magnetic field four times smaller. For dust grains with $1\ \mu\text{m}$ diameter, $0.1\ \text{eV}$ average kinetic energy and $1.05\ \text{g cm}^{-3}$ mass density (polystyrene) in $0.10\ \text{T}$ magnetic field where the relative grain-surface potential is $-7.5\ \text{V}$, the dust-grain gyroradius is $7\ \text{cm}$. Thus, the gyroradius is 5% of the Gold Tank's plasma diameter of $1.5\ \text{m}$, easily satisfying the magnetized-dusty-plasma criterion and allowing the magnetic-field strength to be varied over a wide range in the proposed experiments without violating the criterion. Using a grain diameter ten times smaller would get the gyroradius below 1.5% of the plasma diameter and using a grain diameter ten times larger would keep the gyroradius less than 15% of the plasma diameter. This range of particle diameters ($0.1\text{--}10\ \mu\text{m}$), which are commercially available, is planned for the experiments.

The Gold Tank, shown in figures 3 and 4, is designed to produce large-volume, quiescent, magnetized dusty plasma suitable for studying the dynamical role that dust can play in equilibria, resonances and instabilities when the dust grains are magnetized and in the gaseous dusty-plasma phase. The steady-state plasma is formed by collisional ionization of neutral argon atoms by primary electrons that are thermionically emitted from the filaments behind a concentrically segmented mesh. The secondary population of electrons created by these collisions supplies the plasma electrons. The ions ($T_i = 0.03\ \text{eV}$) and secondary electrons ($T_e = 2.5\ \text{eV}$) form a

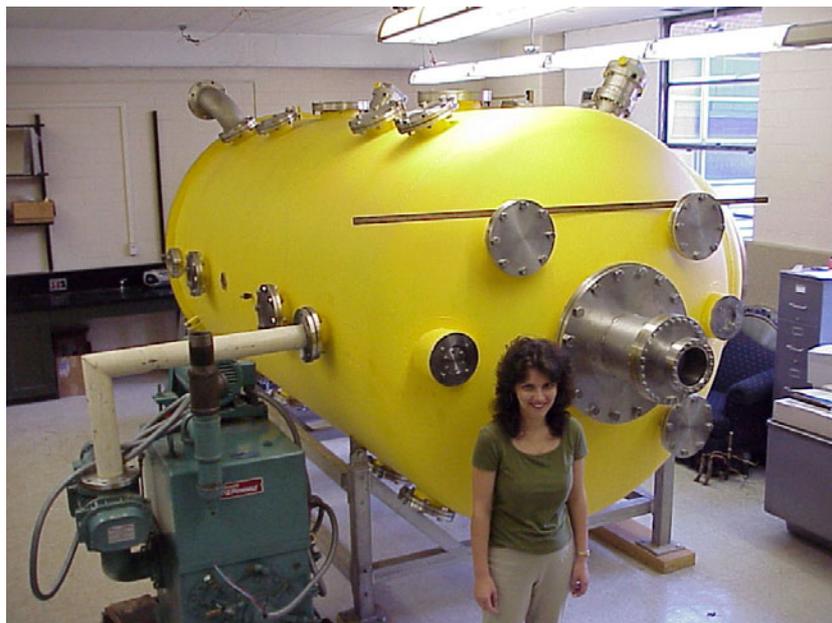


Figure 4. Photograph of the Gold Tank during construction. Note two turbomolecular pumps on the top right ports and an auxiliary pump in the left foreground. Graduate student Ms Raluca Teodorescu is in the centre and a 2 m stick lies across two end ports, aligned with the rightmost edge of the chamber's cylindrical wall.

cylindrical, quasineutral plasma (with density $n \approx 10^7\text{--}10^{12}\text{ cm}^{-3}$). This source design has been refined in the dust-free WVU Q machine at 1/15 scale, but at the proper 1 kG magnetic-field strength.

The primary physics issue to be addressed is the role of non-delta-function (polydisperse) distributions in dust-grain size, charge, mass and shape in magnetized dusty-plasma behaviour. Experiments can be repeated, each time using different specific size and shape distributions within a wide range. The results should contribute to the understanding of the role of polydispersion since, in theoretical models of magnetized dusty plasma, the inclusion of polydisperse distributions has been limited [52]–[54].

Secondary issues are the structure and structuring processes of the dust in the column and the excitation threshold and mode structure of various waves. Magnetized dusty-plasma behaviour that is influenced by the dust-grain charging process is of special interest. The equilibrium results can be compared to [55]–[60] and [61]. The instability results can be compared to [47] and [62]–[67]. Although the models cited have contributed significantly to the present understanding of magnetized dusty plasma, the lack of laboratory experiments from which to derive physical insight seriously weakens the confidence in this understanding.

Oya *et al* [68] report observations in comets of various plasma waves, including ion-cyclotron waves. The dynamics of magnetized dust may be responsible for the observed structure in the comet's dust tail [69]; D'Angelo [47] considered the excitation of dust-cyclotron waves in dusty-plasma conditions resembling the conditions found in comet tails. D'Angelo [47] calculates the excitation-threshold parameters and estimates that the 4 km s^{-1} drift of the ion population past the dust population, although well below the solar-wind speed, is more than

sufficient for exciting the electrostatic dust–cyclotron (EDC) mode. It is worth noting that D’Angelo [47] points out that the excitation threshold for the EDC instability is several times smaller than that for the dust-acoustic instability [70].

Small dust grains make up the bulk of Jupiter’s gossamer ring [71]. Such small grains are easily magnetized and exhibit radial oscillations in their orbital trajectory around the planet. These radial oscillations arise from gyromotion and are affected by the charge-to-mass ratio, by the charging cycle as the grain moves through the plasma environment and by phase shifts between the grain charging cycle and the cycle associated with the grain surface potential. These phase shifts are caused by the finite charging rate and result in a modification to the usual $E \times B$ drift. This modification, known as gyrophase drift, is in the radial direction [72, 73] and should be readily observed in the Gold Tank.

5. Instabilities in magnetized dusty plasma

Both the dust–drift and dust–cyclotron instabilities are driven by current, i.e., a relative drift between the electron and dust populations or between the ion and dust populations. When the voltage of a terminating electrode, at the opposite end of the chamber from the plasma source, is positive relative to the cathode voltage, the electrons drift (with respect to the ions) parallel to the magnetic field, from the source to the terminating electrode. A typical value of parallel electron drift speed achievable with such a biased disc electrode is three times the ion thermal speed [74]. This exceeds by two orders of magnitude the dust–drift or dust–cyclotron excitation threshold in the drift speed, which is approximately an order of magnitude larger than the dust thermal speed [47]. The parallel electron drift speed is determined from the electron current collected by a planar electrode [75, 76]. The parallel ion drift speed is determined from the ion velocity distribution measured using laser induced fluorescence [38].

The EDC instability has been discussed theoretically by D’Angelo [47, 62, 65, 66]. The EDC instability is analogous to the electrostatic ion–cyclotron (EIC) instability [77]–[79], with the charged dust grains and the ions playing analogous roles in the two instability mechanisms. Analogously, the EDC mode frequency is predicted to be 10–20% above the dust–cyclotron frequency, whereas the EIC mode frequency is 10–20% above the ion–cyclotron frequency. The EDC instability should not be confused with the dust–ion–cyclotron (EDIC) instability for which the dust is present but dynamically idle. The EDIC instability has been discussed theoretically [66, 80] and even studied in the laboratory [45]. The Gold Tank configuration can help quantify the meanings of cyclotron resonance and absorption in a magnetized dusty plasma with a polydisperse population of dust. This wave–particle interaction differs conceptually from the case of conventional plasma with two distinct values of the charge-to-mass ratio.

Besides satisfying the magnetized-dusty-plasma criterion, the quantity $k_{\perp}r_d$ should be on the order of unity so the wave can sample the details of ion motion [47]. For values of $k_{\perp}r_d$ smaller than unity, approximations commonly made in modelling the instability theoretically become more valid, but this is not an experimental requirement. The value of k_{\perp} in the proposed EDC-wave experiments can be anticipated based on previous EIC-wave experiments [77, 81], where the radial mode structure of EIC waves was either a standing wave pattern with $k_{\perp} = 2.4/r_c$ or a propagating wave pattern with $k_{\perp} = 2\pi/r_c$, and on previous EDIC-wave experiments [45], where $k_{\perp} = 2\pi/r_p$. The parameter r_c is the radius of the circular, current-collecting electrode used to excite the mode, whereas r_p is the radius of the plasma column. Since the current-channel radius in the Gold-Tank plasma should be a factor of two or more smaller than the plasma-column

radius [82], the two expressions are comparable, $2.4/r_c \approx 2\pi/r_p$. Thus, we use $r_p = 0.75$ m to obtain a lower limit of $2\pi/r_p = 0.084 \text{ cm}^{-1}$ for k_{\perp} . For an upper limit, the expression $k_{\perp} = 2\pi/r_c$ is used. It is noted that EIC wave amplitudes maximize for $r_c = 3.5r_i$ [83], so we take $r_c = 3.5r_d$ to yield $k_{\perp}r_d = 1.8$, independent of magnetic-field strength. Thus, at $B = 0.08$ T, when $r_d = 3.6$ cm, $0.3 < k_{\perp}r_d < 1.8$ and, at $B = 0.03$ T, when $r_d = 10$ cm, $0.8 < k_{\perp}r_d < 1.8$. In both limits of magnetic-field strength, the criterion $k_{\perp}r_d \approx 1$ is met.

6. Conclusions

We will combine the benefits of using Q-machine plasma with the orientation of a horizontal termination electrode (vertical plasma column) to electrostatically and indefinitely confine a quiescent plasma in the vertical Q machine to study the phase transition between dust–crystal and dust–fluid equilibria. The quiescent dusty-plasma equilibrium obtainable in a vertical Q machine is designed for the convenient and independent adjustment of the background neutral pressure and the magnitude, direction and inhomogeneity of ion-relative-to-dust streaming. These capabilities can permit a detailed investigation into the two dominant processes influencing the dusty-plasma equilibrium.

We will apply a strong magnetic field to a discharge plasma, supplied with dust from a tray, to magnetically and indefinitely confine a large dusty plasma in the Gold Tank. The magnetized-dusty-plasma criterion will be achieved in the Gold Tank by using a relatively small dust-grain diameter ($0.1\text{--}1 \mu\text{m}$), a relatively large electron temperature (2.5 eV), a relatively large magnetic-field strength (0.10 T) and a relatively large plasma-column diameter (1.5 m) to minimize the grain mass, maximize the grain charge, maximize the Lorentz force and maximize the plasma-column diameter, respectively. These factors maximize the ratio of plasma-column diameter to dust-grain gyroradius and allow the ratio to exceed unity by almost two orders of magnitude.

Acknowledgments

Assistance with device construction, presently underway, from M Woehrman, A Steele, R Teodorescu, C Teodorescu, S Finnegan and E Reynolds is gratefully acknowledged. Useful discussions with R Merlino, E Thomas and J Spann are gratefully acknowledged. This work was supported by the National Science Foundation.

References

- [1] Rynn N and D'Angelo N 1960 Device for generating a low temperature, highly ionized cesium plasma *Rev. Sci. Instrum.* **31** 1326
- [2] Alexeff I and Pace M 1994 A dust plasma *IEEE Trans. Plasma Sci.* **22** 136
- [3] Sheehan D P, Carillo M and Heidbrink W 1990 Device for dispersal of micrometer- and submicrometer-sized particles in vacuum *Rev. Sci. Instrum.* **61** 3871
- [4] Xu W, D'Angelo N and Merlino R L 1993 *J. Geophys. Res.* **98** 7843
- [5] Barkan A, D'Angelo N and Merlino R L 1994 Charging of dust grains in a plasma *Phys. Rev. Lett.* **73** 3093
- [6] Selwyn G S, Singh J and Bennett R S 1989 *In situ* laser diagnostic studies of plasma-generated particulate contamination *J. Vac. Sci. Technol. A* **7** 2758
- [7] Tuziuti T and Nakamura Y 1994 *Dusty and Dirty Plasma, Noise, and Chaos in Space and in the Laboratory* ed H Kikuchi (New York: Plenum)

- [8] Walch R, Horanyi M and Robertson S 1994 Measurement of the charging of individual dust grains in a plasma *IEEE Trans. Plasma Sci.* **22** 97
- [9] Sheridan T E, Goree J, Chu Y T, Rairden R L and Kiessling J A 1992 Observation of dust shedding from material bodies in a plasma *J. Geophys. Res.* **97** 2935
- [10] Hazelton R C and Yadlowsky E J 1994 Measurement of dust grain charging in a laboratory plasma *IEEE Trans. Plasma Sci.* **22** 91
- [11] Shiratani M, Fukuzawa T and Watanabe Y 1994 Formation processes of particulates in helium-diluted silane rf plasmas *IEEE Trans. Plasma Sci.* **22** 103
- [12] Böhme W, Köhler W E, Römheld M, Vepřek S and Seeböck R J 1994 Observation of dust particle growth and fallout in rf-excited silane discharges *IEEE Trans. Plasma Sci.* **22** 110
- [13] Stoffels E, Stoffels W W, Vender D, Kroesen G M W and de Hoog F J 1994 Laser-particulate interactions in a dusty rf plasma *IEEE Trans. Plasma Sci.* **22** 116
- [14] O'Hanlon J F, Kang J, Russell L K and Hong L 1994 The effects of electrostatic, molecular drag, and gravitational forces on the behaviour of particle clouds in an rf discharge *IEEE Trans. Plasma Sci.* **22** 122
- [15] Beck S E, Collins S M and O'Hanlon J F 1994 A study of methods for moving particles in rf processing plasmas *IEEE Trans. Plasma Sci.* **22** 128
- [16] Ikezi H 1986 *Phys. Fluids* **29** 1764
- [17] Thomas H, Morfill G E, Demmel V, Goree J, Feuerbacher B and Möhlmann D 1994 Plasma crystal: Coulomb crystallization in a dusty plasma *Phys. Rev. Lett.* **73** 652
- [18] Melzer A, Homann A and Piel A 1996 Structure and stability of the plasma crystal *Phys. Rev. E* **53** 2757
- [19] Thomas H and Morfill G E 1996 Solid/liquid/gaseous phase transitions in plasma crystals *J. Vac. Sci. Technol. A* **14** 501
- [20] Melzer A, Schweigert V A, Schweigert I V, Homann A, Peters S and Piel A 1996 *Phys. Rev. E* **54** 46
- [21] Schweigert V A, Schweigert I V, Melzer A, Homann A and Piel A 1996 Alignment and instability of dust crystals in plasmas *Phys. Rev. E* **54** 4155
- [22] Varma R K 1999 Instabilities of inhomogeneous plasmas streaming relative to inhomogeneous dust distributions *J. Plasma Phys.* **62** 351
- [23] Mamun A A and Shukla P K 2000 Streaming instabilities in a collisional dusty plasma *Phys. Plasmas* **7** 4412
- [24] Chae G-S, Scales W A, Ganguli G, Bernhardt P A and Lampe M 2001 Investigation of a streaming instability due to dust-charge fluctuations *IEEE Trans. Plasma Sci.* **29** 186
- [25] Joyce G, Lampe M and Ganguli G 2001 Particle simulation of dust structures in plasmas *IEEE Trans. Plasma Sci.* **29** 238
- [26] D'Angelo N, Pécseli H L and Petersen P I 1974 The Farley instability: a laboratory test *J. Geophys. Res.* **79** 4747
- [27] Suszcynsky D M, Cartier S L, Merlino R L and D'Angelo N 1986 A laboratory study of collisional electrostatic ion cyclotron waves *J. Geophys. Res.* **91** 13729
- [28] Koepke M E, Zintl M W and Good T N 1998 An effect of neutral collisions on the excitation threshold of electrostatic ion-cyclotron waves *Geophys. Res. Lett.* **25** 3095
- [29] Motley R W 1975 *Q Machines* (New York: Academic)
- [30] Carroll J J III, Koepke M E, Amatucci W E, Sheridan T E and Alport M J 1994 A segmented disk electrode to produce and control parallel and transverse particle drifts in a cylindrical plasma *Rev. Sci. Instrum.* **65** 2991
- [31] Koepke M E, Carroll J J III and Zintl M W 1999 Laboratory simulation of broadband ELF waves in the auroral ionosphere *J. Geophys. Res.* **104** 14397
- [32] Havnes O 1988 A streaming instability interaction between the solar wind and cometary dust *Astron. Astrophys.* **193** 309
- [33] Bharuthram R, Saleem H and Shukla P K 1992 Two-stream instabilities in unmagnetized dusty plasmas *Phys. Scr.* **45** 512
- [34] Rao N N, Shukla P K and Yu M Y 1990 Dust-acoustic waves in dusty plasmas *Planet. Space Sci.* **38** 543
- [35] Rosenberg M 1993 Ion- and dust-acoustic instabilities in dusty plasmas *Planet. Space Sci.* **41** 229

- [36] Hill D N, Fornaca S and Wickham M G 1983 Single-frequency scanning laser as a plasma diagnostic *Rev. Sci. Instrum.* **54** 309
- [37] Joyce G 2002 private communication
- [38] Koepke M, Zintl M W, Teodorescu C, Reynolds E W, Wang G and Good T N 2002 Inhomogenous magnetic-field-aligned ion flow measured in a Q machine *Phys. Plasmas* **9** 3225
- [39] Ishihara O and Sato N 2001 On the rotation of a dust particulate in an ion flow in magnetized plasma *IEEE Trans. Plasma Sci.* **29** 179
- [40] Sato N 2002 Magnetic effects in dusty plasmas *Dusty plasmas in the New Millenium: 3rd Int. Conf. on the Physics of Dusty Plasmas* ed R Bharuthram *et al* (Melville, NY: American Institute of Physics) p 66–73
- [41] Jefimenko O D 2002 Torque exerted by a moving electric charge on a stationary electric charge distribution *J. Phys. A: Math. Gen.* **35** 5305
- [42] Sato N, Uchida G, Kaneko T, Shimizu S and Iizuka S 2001 Dynamics of fine particles in magnetized plasmas *Phys. Plasmas* **8** 1786
- [43] Morfill G E, Thomas H M and Zuzic M 1997 Plasma crystals: a review *Advances in Dusty Plasmas* ed P K Shukla, D A Mendis and T Desai (Singapore: World Scientific) p 99
- [44] Morfill G E 2002 private communication
- [45] Barkan A, D'Angelo N and Merlino R L 1995 Laboratory experiments on electrostatic ion cyclotron waves in dusty plasma *Planet. Space Sci.* **43** 905
- [46] Gandy R, Willis S and Shimoyama H 2001 Initial experiments in the Idaho dusty plasma device *Phys. Plasmas* **8** 1746
- [47] D'Angelo N 1998 Current-driven electrostatic dust–cyclotron instability in a collisional dusty plasma *Planet. Space Sci.* **46** 1671
- [48] Nunomura S, Ohno N and Takamura S 1997 Effects of ion flow by $E \times B$ drift on dust particle behaviour in magnetized cylindrical electron-cyclotron resonance plasmas *Japan. J. Appl. Phys.* **36** 877
- [49] Yokota T 2000 Planetary ring simulation experiment in fine particle plasmas *Phys. Scr.* T **84** 175
- [50] Yokota T 2001 Ring simulation experiment using fine-particle plasmas *IEEE Trans. Plasma Sci.* **29** 279
- [51] Luo Q-Z and D'Angelo N 2000 Observations of dusty plasmas with magnetized dust grains *J. Phys. D: Appl. Phys.* **33** 2754
- [52] Bliokh P, Sinitsin V and Yaroshenko V 1995 *Dusty and Self-Gravitational Plasmas in Space (Astrophysics and Space Science Library vol 193)* (Dordrecht: Kluwer)
- [53] Tripathi K D and Sharma S K 1996 Dispersion properties of low-frequency waves in magnetized dusty plasma with dust size distribution *Phys. Plasmas* **3** 4380
- [54] Cramer N F, Verheest F, Vladimirov S V and Wardle M 2002 Waves in magnetized plasmas with a spectrum of dust sizes *Dusty Plasmas in the New Millenium: 3rd Int. Conf. on the Physics of Dusty Plasmas* ed R Bharuthram *et al* (Melville, NY: American Institute of Physics) pp 281–4
- [55] Mendis D A, Houppis H L F and Hill J R 1982 The gravito-electrodynamics of charged dust in planetary magnetospheres *J. Geophys. Res.* **87** 3449
- [56] Northrup T G and Hill J R 1983 The adiabatic motion of charged dust grains in rotating magnetospheres *J. Geophys. Res.* **88** 1
- [57] Horányi M 1996 Charged dust dynamics in the solar system *Ann. Astron. Astrophys.* **34** 383–418
- [58] Horányi M and Mendis D A 1986 The dynamics of charged dust in the tail of comet Giacobini–Zinner *J. Geophys. Res.* **91** 355
- [59] Goertz C K 1989 Dusty plasmas in the solar system *Rev. Geophys.* **27** 271
- [60] Jana M R, Sen A and Kaw P K 1993 Collective effects due to charge-fluctuation dynamics in a dusty plasma *Phys. Rev. E* **48** 3930
- [61] Mahanta L, Saikia B J, Pandey B P and Bujarbarua S 1996 Dynamics of a magnetized gravitating dusty plasma *J. Plasma Phys.* **55** 401
- [62] D'Angelo N 1990 Low frequency electrostatic waves in dusty plasmas *Planet. Space Sci.* **38** 1143

- [63] Rao N N 1993 Low-frequency waves in magnetized dusty plasma *J. Plasma Phys.* **49** 375
- [64] Shukla P K 1996 Waves in dusty plasmas *The Physics of Dusty Plasmas* ed P K Shukla, D A Mendis and V W Chow (Singapore: World Scientific) p 107
- [65] Rosenberg M and Chow V W 1999 Collisional effects on the electrostatic dust cyclotron instability *J. Plasma Phys.* **61** 51
- [66] Tripathi K D 1999 Waves and instabilities in magnetized dusty plasmas *PhD Dissertation* Department of Physics, Indian Institute of Technology (Delhi)
- [67] Farid T, Mamun A A, Shukla P K and Mirza A M 2001 Nonlinear electrostatic waves in a magnetized dust-ion plasma *Phys. Plasmas* **8** 1529
- [68] Oya H, Morioka A, Miyake W, Smith E J and Tsurutani B T 1986 Discovery of cometary kilometric radiations and plasma waves at comet Halley *Nature* **321** 307
- [69] Ip W-H 1984 Comet-solar wind interactions: a dusty point of view *Adv. Space Res.* **4** 239
- [70] Thompson C, Barkan A, D'Angelo N and Merlino R L 1997 Dust acoustic waves in a direct current glow discharge *Phys. Plasmas* **4** 2331
- [71] Northrup T G, Mendis D A and Schaffer L 1989 Gyrophase drifts and the orbital evolution of dust at Jupiter's Gossamer ring *Icarus* **79** 101
- [72] Goertz C K and Morfill G E 1983 A model for the formation of spokes in Saturn's ring *Icarus* **53** 219
- [73] Bliokh P V and Yarashenko V V 1985 Electrostatic waves in Saturn's rings *Sov. Astron. Engl. Transl.* **29** 330
- [74] Amatucci W E, Walker D N, Ganguli G, Antoniadis J A, Duncan D, Bowles J H, Gavrishchaka V and Koepke M E 1996 Plasma response to strongly sheared flow *Phys. Rev. Lett.* **77** 1978
- [75] Bering E A, Kelley M C and Mozer F Z 1973 Theory and operation of the split Langmuir probe *Planet. Space Sci.* **21** 1983
- [76] Gekelman W and Stenzel R L 1978 Ion sound turbulence in a magnetoplasma *Phys. Fluids* **21** 2014
- [77] D'Angelo N and Motley R W 1962 Electrostatic oscillations near the ion cyclotron frequency *Phys. Fluids* **5** 634
- [78] Drummond W E and Rosenbluth M N 1962 Anomalous diffusion arising from microinstabilities in a plasma *Phys. Fluids* **5** 1507
- [79] Kindel J M and Kennel C F 1971 Topside current instabilities *J. Geophys. Res.* **76** 3055
- [80] Chow V W and Rosenberg M 1995 Electrostatic ion cyclotron instability in dusty plasmas *Planet. Space Sci.* **43** 613
- [81] Rasmussen J J and Schrittwieser R 1991 On the current-driven electrostatic ion-cyclotron instability: a review *IEEE Trans. Plasma Sci.* **19** 457
- [82] Correll D L 1975 Linear and nonlinear aspects of the current-driven ion cyclotron instability *PhD Dissertation* Department of Physics, University of California, Irvine, CA
- [83] van Niekirk E G, Krumm P H and Alport M J 1991 Electrostatic ion cyclotron waves driven by a radial electric field *Plasma Phys. Control Fusion* **33** 375