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Preliminary characteristics of magnetic field and plasma performance in the Magnetized Dusty Plasma Experiment (MDPX)

E. Thomas, Jr.,[1,†] A. M. DuBois,[1] B. Lynch,[1] S. Adams,[1] R. Fisher,[1] D. Artis,[1] S. LeBlanc,[1] U. Konopka,[1] R. L. Merlino,[2] and M. Rosenberg[3]

[1]Physics Department, Auburn University, Auburn, AL
[2]Department of Physics and Astronomy, The University of Iowa, Iowa City, IA
[3]Electrical and Computer Engineering, University of California – San Diego, La Jolla, CA

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The Magnetized Dusty Plasma Experiment (MDPX) device is a newly constructed research instrument for the study of dusty (complex) plasmas. The MDPX device is envisioned as an experimental platform in which the dynamical behavior of all three charged plasma components, the electrons, ions, and charged microparticles (i.e., the 'dust') will be significantly influenced by the magnetic force. This brief paper will provide a short overview of the design, magnetic performance, and initial plasma measurements in the MDPX device.

1. Introduction

Complex (dusty) plasmas are four-component plasma systems that consist of electrons, ions, neutral atoms, and charged microparticles (i.e., 'dust'). The presence of the charged dust particles substantially alters the properties of the plasma. First, the microparticles can acquire charge through the collection of ions and electrons from the surrounding plasma environment – in addition to a variety of other photoemission or thermionic emission processes (Shukla and Mamun 1992). However, it is this collection of plasma particles that modifies the density and potential distribution of the surrounding plasma. Second, the presence of the charged microparticles alters the dynamical processes in the plasma due to their relatively high inertia and variability in their charge. This can take the form of either altering the threshold for certain plasma instabilities, e.g., the current-driven dust ion acoustic (Barkan et al. 1995a) or dust electrostatic ion cyclotron instabilities (Barkan et al. 1996) and can also lead to the generation of entirely new plasma instabilities in which the dust particles are the medium of propagation (Barkan 1995b; Piel et al. 2006). In this manner, a dusty plasma is a new class of plasma system in which the charged microparticles and the surrounding plasma are intimately coupled to each other.

The origins of dusty plasma research began more than three decades ago. At that time, much of the emphasis was placed upon understanding the role of charged dust in astrophysical systems such as the formation of spoke structures in Saturn's rings and the properties of comet tails. Indeed, modern space missions such as *Cassini* (at Saturn) and *Rosetta* (at Comet 67P/Churyumov-Gerasimenko) continue this long

† Email address for correspondence: etjr@auburn.edu

tradition of investigating dusty plasma phenomena within the solar system. What has been learned over the decades from these and other space missions is that it is essential to understand the plasma and radiation environments of the solar system in order to understand the dynamics of interplanetary dust. Moreover, it is the coupling between the plasma, the local magnetic field environment of the planets, and the dust that leads to very complex processes such as the ejection of dust particles from Jupiter (Graps et al. 2000). It has also been suggested that magnetized dust could play a role in determining the collapse of large dust clouds into star systems (Mestel and Spitzer 1956) In addition, a recent experiment onboard the International Space Station showed an enhancement of the coagulation of dust particles when the grains are charged (Ivlev et al. 2002; Konopka et al. 2005a). Therefore, understanding the coupling between dust, plasma, and magnetic fields is a topic that is not only of scientific curiosity but is also the one that may lead to a better understanding of very fundamental processes in the universe.

2. Magnetizing a dusty plasma

Achieving the conditions required to produce a magnetized dusty plasma in the laboratory is technically challenging. This is because of the very low charge-to-mass ratio of the charged dust particles. Consider a laboratory dusty plasma made with argon gas and with typical properties: electron and ion densities, $n_{\mathrm{e}} \approx n_i \sim 10^{14}$ to $10^{16}\mathrm{m}^{-3}$, electron temperature, $T_{\mathrm{e}} \sim 2$ to 5 eV, ion temperature, $T_{\mathrm{i}} \sim 0.025$ eV, and dust density, $n_{\mathrm{d}} \sim 10^9$ to $10^{12}\mathrm{m}^{-3}$. In this system, *a* charged silica ($\rho = 2200$ kg/m^3) microparticle with a radius, $a = 0.5$ micrometers (mass, $m_{\mathrm{d}} \sim 1.15 \times 10^{-15}$ kg) will acquire a net charge of $Z_{\mathrm{d}} \sim 2100$ to 3700 electrons. This means that, relative to the charge-to-mass ratio for an electron $(q_{\mathrm{e}}/m_{\mathrm{e}})$, an argon ion would have $(q_{\mathrm{i}}/m_{\mathrm{i}}) \sim 1.4 \times 10^{-5}(q_{\mathrm{e}}/m_{\mathrm{e}})$ and a microparticle would have a charge-to-mass ratio $(q_{\mathrm{d}}/m_{\mathrm{d}}) \sim 1.7\ \mathit{to}\ 2.9 \times 10^{-12}(q_{\mathrm{e}}/m_{\mathrm{e}})$.

Furthermore, it is common to use the so-called Hall parameter to quantify the degree of magnetization of a plasma. This is given as $\beta = \omega_{cj}/\nu_{nj} \sim B/aP$, where $j = e$, i, d (electrons, ions, dust), which is the ratio of the cyclotron frequency to the neutral momentum exchange frequency; B is the magnetic field strength, a is the radius of the microparticle, and P is the neutral gas pressure. For a plasma species to be considered to be magnetized, the parameter β must be greater than 1 (i.e., $\beta \geqslant 1$). Other considerations such as the ratio of the gravitational force to the magnetic force or the ratio of the gyro-orbit size to the device size all lead to the same result: In order to achieve magnetization, a key requirement is to maximize the ratio of the magnetic field strength to particle size: B/a. It is concluded that, in order to achieve magnetization of the dusty component of the plasma, a combination of large magnetic field strength and small particle size is needed. It is noted, however, that other effects, such as the role of dust–dust collisions may also influence the degree of magnetization of the microparticles. These effects are not yet well understood and will be investigated as part of the study of the magnetized dusty plasma.

Of course, there are practical limits to this result. The generation of large, steady-state magnetic field strengths of several Tesla can be both technically challenging and financially costly. Moreover, the use of very small particles, $a \leqslant 0.5$ micrometers requires careful design of imaging systems in order to be detected. Over the past decade, several groups around the world have built experiments to study the properties of dusty plasmas under the influence of magnetic fields. Table 1 shows a brief summary of the capabilities of these systems. It is noted that with the exception of

Device*	$B_{\max}$ (T)	Dia. (cm)	Axial (cm)	Plasma Source	Refs.
JIHT	0.25	3.6	60	DC	Vasiliev et al. 2011
DUSTWHEEL (Kiel)	0.5	15	67	RF	Knist et al. 2011
Tohoku	4	10	2	DC, RF	Sato et al. 2001
MPE	4	20	20	RF	Konopka et al. 2005b
Suleiman (Kiel)	>4	5	100	RF	Greiner 2012
MDPX	>4	35	200	RF, DC	Thomas 2012

**JIHT: Joint Institute for High Temperatures, Moscow, Russia; Kiel: Kiel University, Germany, Tohoku: Tohoku University, Sendei, Japan, MPE: Max Planck Institute for Extraterrestrial Physics, Garching, Germany.

Table 1. Summary of the parameters of past and current experiments that are investigating the physics of magnetized dusty plasmas.

the experiments at JIHT and DUSTWHEEL (at Kiel University), all of these devices are capable of producing strong magnetic fields of up to 4 Tesla. The MDPX device builds upon the operational regimes of these earlier devices and extends the potential parameter space in which to perform studies of magnetized dusty plasmas.

3. Magnetized Dusty Plasma Experiment (MDPX)

The MDPX device consists of two primary components: a four-coil superconducting magnet system encased in a large cryostat vacuum chamber and an independent plasma chamber vacuum vessel that is inserted into the bore of the magnet. The vacuum chamber design has been described in some detail in an earlier work (Thomas et. al. 2012) and only a brief summary will be given here. This paper will focus on the first measurements and performance characteristics of the magnets.

The MDPX plasma chamber consists of an octagonal-shaped central chamber with cylindrical extensions that can be added to the top and bottom of the chamber. The main chamber consists of an octagonal frame inscribed on an 17-inch (43-cm dia.) circle. The interior of the octagon is cylindrical with a 14-inch (35.6-cm) diameter. The main chamber is 7.5-inch (19-cm) tall and has 5-inch tall × 4-inch wide (12.7 × 10.2 cm) ports. The shape of the vacuum chamber allows excellent optical access to the plasma volume through four pairs of parallel ports. Two 36-inch long, 6 inch in diameter (91.4 × 15.2 cm) cylindrical extensions can be added to the top and bottom of the octagonal chamber to produce a vacuum chamber that is almost 2-m long.

In its initial configuration, a pair of electrodes, 12 inch (30.4-cm) in diameter, are used to produce a radio frequency (RF)-generated plasma using a powered lower electrode and a grounded upper electrode. The lower electrode is 6 inch (15.2 cm) in diameter, and has 1/4-inch (0.64 cm) deep depression at its center to aid in the confinement of the charged microparticles. Initial experiments have been performed, without a magnetic field, to characterize plasma production and the formation of dusty plasmas. Figure 1 shows views of the plasma chamber, a dust particle cloud, and some initial plasma parameter measurements.

The key component of the MDPX device is the superconducting magnet system. The magnet system consists of four coils wound from niobium–titanium superconducting strands that are embedded in copper; each strand is 1.15 mm in diameter. The

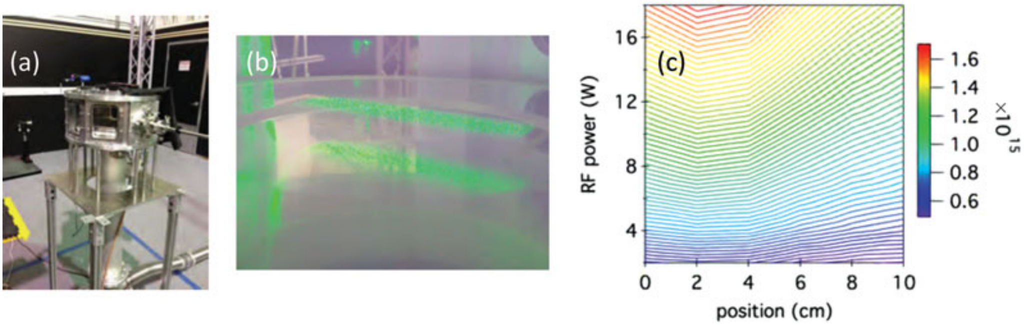

FIGURE 1. (Colour online) (a) A view of the octagonal vacuum chamber with the lower extension attached. (b) A view of a particle cloud illuminated by a green diode laser suspended in the MDPX plasma chamber, the light blue glow is from the background argon plasma. (c) A contour plot showing a range of plasma density measurements as a function of radial position and applied radio frequency (RF) power without a magnet field.

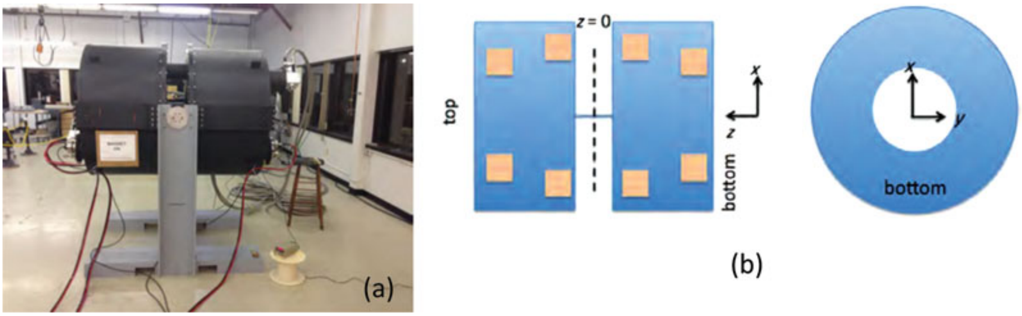

FIGURE 2. (Colour online) (a) Photograph of the MDPX magnet cryostat rotated into horizontal orientation. (b) Schematic drawing showing approximate locations of the coils and the coordinate system that are used for characterizing the magnetic field structure of the magnet system.

arrangement of the four coils is shown in Figure 2. The two larger coils have an inner diameter of 673 mm, outer diameter of 900 mm, an axial length of 129 mm, and 12,428 turns of wire. The two smaller coils have an inner diameter of 560 mm, outer diameter of 686 mm, an axial length of 132 mm, and 7068 turns of wire. This coil system is not only capable of producing a highly uniform magnetic field – a feature in common with the other devices listed in Table 1 – but is also designed to be capable of producing a variable magnetic configuration ranging from linear gradients to a quadrapole-like magnetic field (i.e., a magnetic cusp). The ability to operate with a variety of magnetic field configurations not only adds a new dimension to possible dusty plasma experiments but also may allow a broad range of research on the physics of highly magnetized plasmas.

Initial testing of the coils was performed in December 2013 to evaluate the performance of the system. At the time, the magnets were limited to operating up to a peak field of 2 Tesla because of the presence of magnetic materials in the laboratory. The characterization of the magnetic field was performed at a nominal magnetic field strength of 0.5 Tesla using a Hall probe that was scanned along the z-direction at different x- and y-positions, thereby creating a map of the magnetic field in the central region of the device that extended over 60 cm in the axial direction and a diameter of 20 cm.

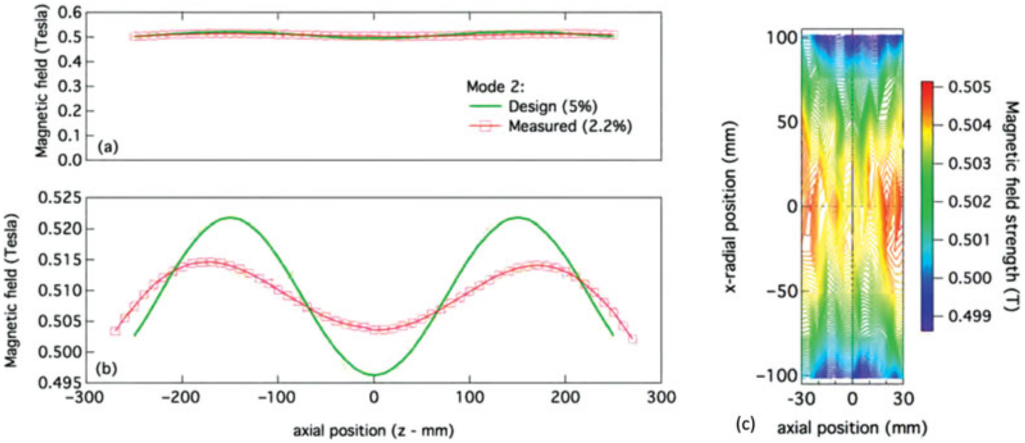

FIGURE 3. (Colour online) (a) Axial measurement of the magnetic field along the center ($x = 0$, $y = 0$) of the magnet. This figure shows the field strength for a nominal setting of 0.5 T. (b) An expanded view of the axial magnetic field to reveal the modulation of the magnetic field strength. The green line shows the predicted ripple of 5% for this configuration. The red squares show that the measured magnetic field has a lower ripple – suggesting that the 'as-built' magnetic field system exceeds the uniformity requirements. (c) Contour plot of the magnet field in the central region of the magnet. This region has an axial extent of 60 mm and a radial extent of 200 mm. The magnet field ripple in this region is 0.95% in the radial direction and 0.2% in the axial direction for a nominal field of 0.5 Tesla.

To characterize the quality of the magnetic field, the magnetic field uniformity is defined using: $\varepsilon = \frac{2(B_{\max}-B_{\min})}{(B_{\max}+B_{\min})}$ for each direction. During the design of the MDPX device, specific targets were given for the magnetic field uniformity. While a complete presentation of the magnetic field measurements is not possible in this short summary paper, however some selected data that highlight the uniformity of the magnetic field is presented in Figure 3. It is shown that the magnet system meets or exceeds the design criteria.

4. Summary

In summary, the MDPX device is the latest in a series of experiments that seek to explore the physics of magnetized dusty plasmas as well as the broader topic of strongly magnetized plasmas. The MDPX device has leveraged the experiences and design features of the earlier devices to develop a new experiment that not only covers a complimentary range of experimental parameters but also extends into a new regime that will enable a broad range of experiments that could include such features as studies of the combination of gyromotion and $\mathbf{E} \times \mathbf{B}$ drifts of charged microparticles, paramagnetic and ferromagnetic particles in magnetic field gradients, and plasma–wall interactions at a range of strike angles.

This paper has presented early measurements of the plasma parameters that have been measured in the MDPX plasma chamber. These measurements show that, in the absence of a magnetic field, the plasma parameters are quite typical for a dusty plasma experiment. In addition, this paper has presented initial measurements of the magnetic field for operations in the range $B = 0.5$ Tesla. These measurements are shown to meet or exceed the design characteristics for the MDPX device.

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