Design Criteria for the Magnetized Dusty Plasma eXperiment

Edward Thomas, Jr., Robert L. Merlino, and Marlene Rosenberg

***Abstract*—This paper discusses the design of the new Magnetized Dusty Plasma eXperiment (MDPX) device that is currently under construction at Auburn University. This device, which is envisioned to be operated as a multiuser facility, has incorporated many of the features of current dusty plasma experiments that make use of strong magnetic fields while adding new features—such as an extended plasma volume, programmable linear magnetic field gradients, and variable magnetic field geometries—that will greatly extend the operating space of the new device. This paper discusses the physics criteria used to define the operating parameters of the MDPX device and presents a discussion of the initial configuration of the experiment.**

***Index Terms*—Dusty plasma, magnetic field, magnetized dusty plasma.**

I. INTRODUCTION

FOR OVER 20 years, there has been an active experimental program that has investigated the properties of complex (dusty) plasmas. These four-component plasma systems consist of neutral atoms, ions, electrons, and charged microparticles. The experimental attractiveness of these systems arises from the fact that the microparticles—which are typically a few hundred nanometers up to a few micrometers in radius—can be directly visualized using relatively simple light scattering techniques. The large mass of the microparticles, as compared to that of the electrons or ions (where $m_{\rm dust} > 10^{12}\ m_{\rm ion}$), allows many of the dynamical effects of a dusty plasma to occur on time scales of milliseconds or longer. This allows phenomena to be observed using "high-speed" imaging techniques—but at modest rates of just a few hundred frames per second.

While the large mass of the microparticles certainly offers certain experimental advantages, it can also introduce disadvantages as well. In particular, consider the motion of a charged microparticle in a magnetic field. Using orbit-motion-limited charging models, it is possible to make an estimate of the charge that can be collected on an electrically floating microparticle in a plasma. For typical laboratory parameters of electron plasma density $n_e \sim 10^{15}$ m^{-3} and electron temperature $T_e \sim 3$ eV, silica microparticles (mass density of 2000 kg/m^3) with a radius of $r_d \sim 0.5\ \mu$m will acquire a negative charge $Z_d \sim 1000$ electrons. Here, the dust grain charge is given by $q_d = Z_d e$, where e is the elementary charge on an electron. Therefore, if the charge-to-mass ratio for an electron is defined as one, then for a singly charged argon ion, it would be 1.4×10^{-5}, and for a 0.5-μm-radius dust grain, it would be 6.6×10^{-12}.

These calculations give some insight into the experimental challenges related to the study of charged microparticles in plasmas with magnetic fields. Because the charge-to-mass ratio for the microparticles is small, the dust grain gyrofrequency, which is given by $\omega_{cd} = q_d B/m_d$, may be lowered to a regime that is accessible to video imaging technologies (which is an experimental advantage). However, the dust grain Larmor (gyro-)radius, which is given by $\rho_d = v_d/\omega_{cd} = m_d v_d/q_d B$, can become quite large (which is an experimental disadvantage). Here, B is the magnetic field strength, m_d is the dust particle mass, and v_d is the dust particle velocity.

The presence of a magnetic field can alter many of the fundamental properties of the plasma—from the charge density distribution to the transport of charged particles, to the generation of plasma instabilities. For a dusty plasma, the presence of a magnetic field introduces an important new parameter that is expected to significantly modify its properties. This paper discusses the development of a new Magnetized Dusty Plasma eXperiment (MDPX) that is currently under construction at Auburn University. Specifically, this paper will focus on two particular aspects of this new experiment: 1) the design criteria that are used to prescribe the operating parameters for the device and 2) using those criteria to motivate the design of the device.

II. DESIGN CRITERIA

The MDPX follows a development path that has been ongoing for about ten years. Early attempts at performing experiments where the dynamics of the charged microparticles was modified by the magnetic field were first reported in Japan [1], [2] and Russia [3]. These experiments, which were operated at magnetic field strengths up to 2.5 T, gave the first evidence that, as the ion and electron dynamics are modified by the magnetic field, there is a corresponding change in the dynamics of the charged microparticles. The effects reported in these studies generally focused on the changes to the shape of the microparticle clouds and the rotations of the cloud structures.

Additionally, another early experiment reported by Samsonov *et al.* [4] discussed the behavior of a complex plasma

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composed of paramagnetic particles. In this study, the confinement of the suspended particles was modified by the addition of a magnetic field gradient that allowed particles to become levitated at a new location in the plasma. Here, the magnetic gradient force was used to partially compensate for the gravitational force.

The results of those early studies have continued to motivate the dusty plasma community and have led to the development of dedicated experimental devices whose mission is to study a fully magnetized dusty plasma. In particular, experimental devices are now in operation at the Max Planck Institute in Garching, Germany [5], and at Kiel University in Kiel, Germany [6]. Both of these devices produce uniform magnetic fields with a magnitude $B \sim 4$ T.

Over the last three years, a development path has been undertaken to build an MDPX that is based in the U.S. This device has been conceived to be a part of a multiuser midscale research facility that builds upon the lessons learned from the international community. This development path has, at its core, two important scientific goals for the MDPX device.

The first goal is to build a device that is capable of producing a magnetic field strength such that the magnetic force on the charged microparticles would be comparable to the other dominant forces (e.g., Coulomb interdust force, neutral drag, and ion drag) that are acting upon the microparticles. The second goal is to extend the operating regime of a magnetized dusty plasma beyond studies of particles in uniform magnetic fields to regimes where magnetic field gradients can play an important role in the dynamics of the plasma.

To achieve these goals, the MDPX device has built upon the features and capabilities of existing high-magnetic-field dusty plasma experiments. It broadens the range of magnetized dusty plasma studies by including these features:

1) generating an extended plasma length of $\geq$2 m to allow studies of new dusty plasma waves such as the electrostatic dust cyclotron wave [7]–[9];
2) generating "operator-defined" magnetic field gradients;
3) operating with a range of magnetic field geometries;
4) providing expanded direct diagnostic access to the plasma volume, particularly along the midplane of the device.

To design the MDPX device with the capabilities and the two scientific goals defined earlier, it is necessary to define several key quantities that can be used to specify the parameters of the experiment. The authors considered a broad range of dimensionless ratios but eventually came to focus on two important ratios for quantifying the behavior of the charged particles in *uniform* magnetic fields. The first ratio R_g is a geometric consideration that compares the Larmor (gyro-)radius of the particle (ρ_d) to the scale size (e.g., one-tenth the radius of the vacuum chamber) of the experiment (L). For the dust particles to be considered as "magnetized," this ratio should be much less than one

$$R_g = \frac{\rho_d}{L} = \frac{m_d v_d}{q_d B L}. \tag{1}$$

The second ratio R_c arises from the competition between the magnetic force on the particle and the drag due to collision and is given as the ratio of the dust gyrofrequency to the dust–neutral collision frequency. For this ratio, the condition for magnetization requires that this ratio be greater than one

$$R_c = \frac{\omega_{cd}}{v_{dn}} = \frac{q_d B/m_d}{\left(\frac{4\pi}{3}\delta\frac{m_n N_n v_{tn} a^2}{m_d}\right)}. \tag{2}$$

In these equations, m_n is the mass of the neutral gas atoms, N_n is the number density of the neutral gas which is directly proportional to the gas pressure P, v_{tn} is the thermal velocity of the neutral gas atoms, and δ is a numerical constant for the Epstein drag force which is $\sim$1–2. Additionally, in the aforementioned models, it is assumed that the dust grains are spherical particles such that the dust grain mass $m_d \sim a^3$, where a is the dust particle radius. Furthermore, assuming that the grains are charged according to the orbit-motion-limited theory, the dust grain charge is given by a spherical capacitor model as

$$q_d = 4\pi\varepsilon_0 a \Phi_d \tag{3a}$$

$$\Phi_d = f(n_e, T_i, T_e, n_d, v_d, B). \tag{3b}$$

It is noted that the complexity in this model arises from the fact that the dust grain surface potential Φ_d is a complex function of the surrounding plasma that is computed from the flux of ions and electrons to the dust grain as described extensively in the literature [10], [11].

When (1) and (2) are combined with the dust grain mass approximation and (3), the two ratios can be reduced to the scaling relations shown in

$$R_g \sim \frac{a^2 v_d}{B} \ll 1 \tag{4a}$$

$$R_c \sim \frac{B}{aP} > 1. \tag{4b}$$

The scaling relations given in (4) show common results for operations in uniform magnetic fields. In order to achieve the operational conditions necessary to achieve the scientific goals of the MDPX project, the ratio of magnetic field strength to dust particle radius B/a should be maximized. Alternatively, the experiment should be designed to operate with a combination of large magnetic field strengths and small particle sizes in order to ensure the broadest possible operating space.

Figs. 1 and 2 illustrate the magnetization criteria specified in (4) for 1-μm-diameter particles that have a surface charge $Z_d = 2080$ and are traveling with a thermal speed of $v_d =$ 5 mm/s (assuming that the dust grains have a kinetic temperature approximately equal to room temperature). Fig. 1 gives an estimate of the gyroradii of silica and melamine particles as a function of magnetic field strength. Fig. 2 gives an estimate of the dust collisionality ratio R_c as a function of magnetic field strength for the same particles used in Fig. 1. Because R_c is not dependent upon the particle mass, the results shown here are applicable to either a silica or a melamine particle. Both figures show that minimum magnetic field strengths of $|B| \sim 1{-}2$ T (depending upon the neutral gas pressure) are required in order to ensure that both criteria defined by (4) are satisfied.

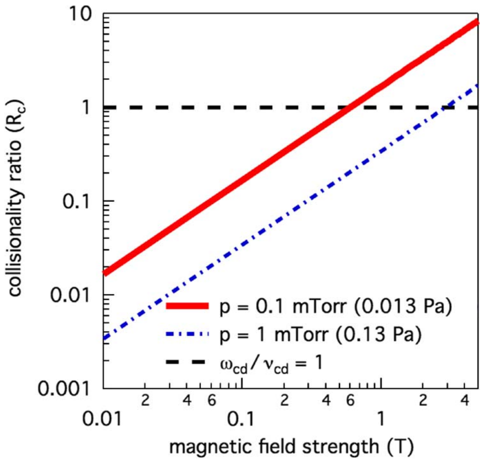

Fig. 1. Scaling of the dust gyroradius of a 1-μm-diameter microparticle at a velocity of 5 mm/s as a function of magnetic field strength. The red and blue lines represent the motions of the silica (mass density $\rho = 2200$ kg/m^3) and melamine ($\rho = 1510$ kg/m^3) particles, respectively. The dashed horizontal line represents a gyroradius that is one-tenth the radius of the plasma chamber.

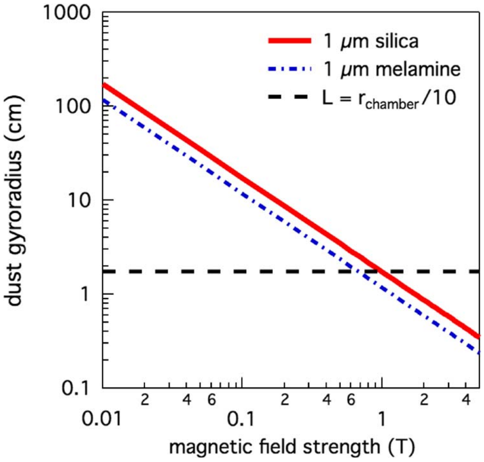

Fig. 2. Scaling of the collisionality ratio R_c as a function of magnetic field strength for different neutral gas pressures. The red and blue lines represent neutral gas pressures of 0.1 and 1 mtorr, respectively. The dashed horizontal line represents $R_c = 1$. For the charged dust particles to be considered magnetized, $R_c \geq 1$.

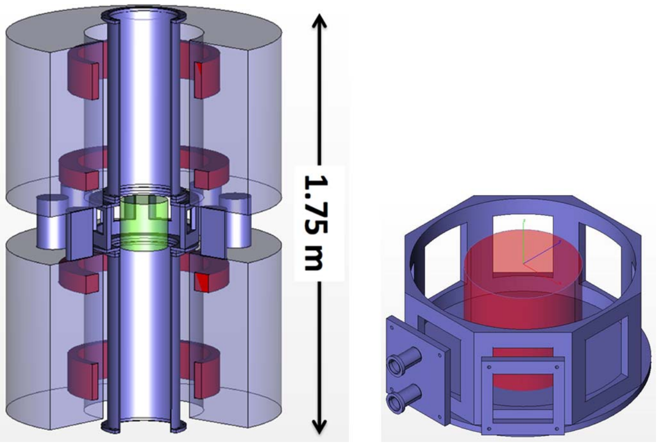

Fig. 3. Schematic drawing of the MDPX device. (Left) Cutaway drawing of the vacuum vessel with its extensions is shown. The magnets are shown as the red coils. The green section in the center is the extent of the uniform region. (Right) Expanded view of the central octagonal vacuum chamber with representative ports for a probe and a window. Here, the red cylinder indicates the location of the uniform magnetic field region.

For experiments involving magnetic field gradients, it is necessary to modify the operational criteria. For example, in the earlier experiment by Samsonov *et al.*, it was shown that, in the presence of a gradient, paramagnetic particles (i.e., particles with a magnetic susceptibility $\mu > 1$) can be transported to regions of local maxima in the magnetic field. An estimate for the force on a paramagnetic particle F_m can be compared with the gravitational force $F_g = m_d g$

$$\frac{F_m}{F_g} = \left(\frac{4\pi}{\mu_0}\right)\left(\frac{\mu - 1}{\mu + 2}\right)\frac{a^3 B \nabla B}{m_d g}. \tag{5}$$

Here, μ_0 is the permeability of free space, a is the radius of the microparticle, and g is the acceleration due to gravity. For a 1-μm-diameter paramagnetic silica microparticle with $\mu = 1.05$ in a $B = 0.5$ T magnetic field and using the ratio given in (5), the required magnetic field gradient to balance the gravitational force would be $dB/dz \sim 1$ T/m. Under the same conditions, for a microparticle with a superparamagnetic coating (i.e., $\mu = 3$), the required magnetic field gradient would be reduced to $dB/dz \sim 0.05$ T/m. This defines a range of conditions that would be of great interest to study in the MDPX.

III. MDPX Device Parameters

Using the results of calculations like those illustrated in Figs. 1 and 2, it is possible to define the parameters of the MDPX device. This design is the result of a community-wide discussion that solicited input from the present MDPXs. The result of these discussions has been the development of a "Day One" experimental configuration for the MDPX device. It is anticipated that, over time, these operating conditions will evolve as users gain experience with the device. The MDPX device consists of two main components: the electromagnets and the plasma chamber. Each of these components and the diagnostic systems will be described in the following. A schematic drawing of the MDPX device is shown in Fig. 3.

The magnetic field in the MDPX device will be generated using four independently powered superconducting coils. The coils are fabricated from a NbTi superconducting wire that will carry a maximum current of 120 A and have a peak current density of $\sim 10\,000$ A/mm^2. The magnet assembly will have an inner diameter (warm bore) of 50 cm, a length of 175 cm, and an outer diameter of 125 cm. The coils are designed to operate in four basic operational modes:

1) *mode 1*: a highly uniform high-magnetic-field mode with $|B| \geq 4$ T over a 20-cm-diameter 20-cm-long axial region with a field uniformity of 1% or less;
2) *mode 2*: an extended uniform high-magnetic-field mode with $|B| \geq 4$ T over a 20-cm-diameter 50-cm-long axial region with a field uniformity of 5% or less;
3) *mode 3*: a linearly varying magnetic field configuration that allows programmable axial gradients of

0.05 T/m $\leq |dB/dz| \leq 1$ T/m at magnetic field strengths ranging $0.02 \leq |B| \leq 1$ T;

4) *mode 4*: a magnetic "cusp" configuration achieved by operating the "upper" and "lower" magnetic field coils with currents in the opposite direction to allow shaping of magnetic field geometry in the central region of the experiment.

It is noted that modes 3 and 4 are the unique operating configurations for the MDPX device that will allow access to operational regimes that are presently inaccessible in current experiments.

In addition to the new magnetic field configurations used for the MDPX device, another important requirement is to expand the diagnostic access to the plasma volume. With the expanded access, a variety of different diagnostic systems can be used. These include the following:

1) *in situ* Langmuir probes (electron density, electron temperature, and plasma potential);
2) laser-induced fluorescence (ion density, ion temperature, and ion flow velocity);
3) particle image velocimetry (dust transport and dust thermal properties);
4) high-speed imaging (dust transport).

The MDPX device is designed using an octagonal arrangement as shown in Fig. 3. The main ports are large [15.2 cm by 16.5 cm (6 in by 6.5 in)], allowing considerable optical access to the plasma. Additionally, the ports have adaptor flanges that allow standard ISO-style vacuum flanges to be used on the device. The chamber has an outer diameter of 43.2 cm and an inner diameter of 35.6 cm. The chamber has an axial extent of 20 cm. Additionally, two cylindrical extensions, each 100 cm long and 15 cm in diameter, can be added to the main chamber to create a plasma length of just over 2 m long.

For the initial operation of the MDPX device, it was decided to use an experimental configuration that would initially allow direct comparisons to be made with the other operating MDPXs. As a result, initial operations of the MDPX device will use a parallel-plate RF glow discharge configuration for its initial experiments. The estimated plasma parameters that can be expected in the MDPX device using this configuration—for moderate RF input powers of 20 W or less—are given in Table I.

It is noted that, with the use of this configuration, at higher magnetic field strengths ($B \geq 2.5$ T), there are observations of plasma filamentation [12]. While some preliminary work suggests that increased spacing between the RF electrodes or gas pressure can be used to mitigate these effects, it is likely that some development work will be needed to either find operational configurations that avoid the filamentation or develop new types of plasma sources that are not subject to this effect.

IV. CONCLUDING REMARKS

The MDPX device represents the next generation of MDPXs that builds extensively on the experience and knowledge gained from a broad range of dusty plasma studies from around the world. This new facility, which is currently under construction, has already begun initial tests of plasma generation and characterization and will continue these benchmarking studies through the end of 2012. Magnet delivery is anticipated in spring 2013 with integrated operation of the MDPX device beginning in summer 2013. It is hoped that this new experimental facility will provide expanded research opportunities for the dusty plasma community for many years to come.

TABLE I
TYPICAL PLASMA PARAMETERS FOR THE MDPX DEVICE

Plasma parameters

Gas	argon (A = 40)	Electron Debye length (λ_{De})	~0.3 to 0.5 mm
Pressure (p)	1 mTorr	Ion Debye length (λ_{Di})	~0.04 mm
Electron temp. (T_e)	2 to 5 eV	Mean free path (neutrals) (λ_{mfp})	60 mm
Ion temp. (T_i)	1/40 eV	Ion gyro-radius (@ B = 2 T) (r_{Li})	0.05 mm
Density ($n_i \approx n_e$)	10^{15} m^{-3}	Electron gyro-radius (@ B = 2 T) (r_{Li})	0.002 mm

Dust parameters

Dust material	silica $\rho = 2000$ kg/m^3	Dust charge (a = 500 nm) (Z_d)	-2000 ± 100
Dust density (n_d)	1.5 x 10^{10} m^{-3}	Dust charge (a = 100 nm) (Z_d)	-400 ± 50
Inter-particle spacing (Δ)	0.25 mm	Dust drift velocity (v_d)	5 mm/s

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