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Magnetized dusty plasmas: the next frontier for complex plasma research

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Abstract
This paper discusses the role of magnetic fields in dusty (complex) plasma experiments. It first provides a description of the conditions necessary for a dusty plasma to become fully magnetized. The paper then briefly reviews a series of experimental studies that illustrate how magnetic fields are applied to dusty plasmas—from experiments that use magnetic fields to control the background plasma to those that have strong enough magnetic fields to directly modify the confinement and dynamics of the charged microparticles. The paper will then discuss the newest experiment that is currently under development at Auburn University, the magnetized dusty plasma experiment device. The paper concludes with a discussion of important outstanding physics and technical issues that will define the next generation of experiments.

(Some figures may appear in colour only in the online journal)

1. Introduction

Plasmas, charged microparticles and magnetic fields are ubiquitous in the visible universe. In environments as diverse as planetary rings to fusion experiments, the interaction of ionized gas with magnetic fields and charged particulate matter (i.e. the 'dust grains') can have a profound impact on the plasma environment. Consider, for example, the transport of particulate matter across magnetic field lines into the core plasma. Here, the presence of the microparticle represents a potential sink as energy from the plasma is used to heat and vaporize the material in addition to radiative losses as the impurity atoms are ionized. Moreover, very fundamental astrophysical questions, such as what are the processes responsible for the earliest stages of planetesimal formation in proto-planetary discs, remain a topic of critical importance for understanding the basic process in the universe. In both of these cases—and many more physical processes, how the presence of the magnetic field alters the coupling between the plasma and the charged microparticles remains poorly understood.

To date, laboratory dusty (complex) plasma research has been focused on the dynamics of charged microparticles in plasma environments without the presence of magnetic fields. For the vast majority of these studies, it is the competition between the gravitational and electric forces that defines the zero-order equilibrium; i.e. in order to suspend microparticles in a plasma, the downward gravitational force on the particles must be compensated by other forces. Once suspended in the plasma, the resulting particle dynamics are driven by inter-particle electrostatic forces (e.g. screened Coulomb), neutral drag forces and ion drag forces. However, in the presence of a magnetic field, all forces that act upon the dust grains that are dependent upon the charge can potentially be modified. Moreover, the charging mechanism of the dust grains themselves will also be modified by the magnetic field as the ion and electron dynamics become dominated by the magnetic forces acting upon them. Finally, at a sufficiently large magnetic field strength, the direct magnetic force acting upon the dust grains can become comparable to the other forces that are acting upon it.

This paper gives a brief review of the progress towards the development of a fully magnetized dusty/complex plasma. For the purposes of this paper, a 'fully magnetized dusty plasma' will be defined as a plasma system consisting of ions, electrons, neutral atoms and charge microparticles in which the magnetic

Table 1. Operating parameters for a glow discharge laboratory dusty plasma.

Parameter	Range	Operational value
Plasma		
Plasma density ($n_e \sim n_i$)	10^8–10^{11} cm^{-3}	10^{10} cm^{-3}
Electron temperature (T_e)	1–10 eV	3 eV
Ion temperature (T_i)	—	0.025 eV
Gas species	N_2, Ne, Ar, Kr	Ar ($A = 40$)
Neutral pressure (p)	0.001 to 200 Pa	0.13 Pa
Dust particles		
Mass density – melamine formaldehyde (ρ_d)	—	1500 kg m^{-3}
Number density (n_d)	(0.1–5.0) $\times 10^4$ cm^{-3}	10^4 cm^{-3}
Radius (a)	0.25–5 μm	0.5 μm
Number of electrons/particle (Z_d)	800–10 000	1000

force on the dust grains can be comparable in strength to the other forces that are affecting it. Such a system will have a progression of operating regimes where first the electrons, then the ions, and finally the charged microparticles would have their dynamics controlled by the magnetic force.

This paper is organized in the following manner. Section 2 will discuss the experimental conditions necessary to create a magnetized dusty plasma. Section 3 will describe earlier complex plasma experiments that have made use of magnetic fields. First, a description will be given of those experiments in which the magnetic fields are used primarily to control the ion and electron properties. This will be followed by descriptions of the two currently operating, high magnetic field dusty plasma devices (DPDs)—one located at Kiel University (Kiel, Germany) and the other located at the Max Planck Institute (Garching, Germany). Section 4 will then describe the current development status of a new magnetized dusty plasma experiment (MDPX) device that is currently under construction at Auburn University (Alabama, USA) that is designed to extend the operational space for these experiments. Finally, section 5 will discuss some of the research opportunities that are enabled by the investigation of fully magnetized dusty plasmas.

2. Magnetizing a complex plasma

Before discussing the range of experiments that have attempted to study the influence of an external magnetic field on a dusty plasma, it is first necessary to understand the technical challenges associated with creating a fully magnetized dusty plasma. One of the first challenges arises from the charge-to-mass ratio of the different components in the plasma.

The majority of laboratory dusty plasma experiments in operation today are produced under glow discharge plasma conditions. A summary of the plasma parameters for this experimental configuration is given in table 1. Consider a dusty plasma is created using the 'operating values' from table 1. Under these conditions, let the charge-to-mass ratio for an electron (e/m_e) be normalized to a value of 1. Then, for a plasma consisting of argon ions, the charge-to-mass ratio of a singly ionized argon ion (as compared with the electron) would be $e/m_i = 1.4 \times 10^{-5}$. A 1 μm diameter, spherical silica microparticle placed in this plasma will acquire a net negative charge of $Z_d \sim 1000$ electrons; where the dust charge ($q_d = -Z_d e$). For this microparticle, the normalized charge-to-mass ratio (compared with the electron) would be $q_d/m_d = 9.6 \times 10^{-12}$. This very small charge-to-mass ratio of the dust particles has important consequences when attempting to define the criteria for magnetizing the charged microparticles in a dusty plasma.

To define magnetization, there are a number of factors that could be considered such as the size of the Larmor orbit, the size of the experiment, the strength of the magnetic force, collisionality and many other factors. For the purposes of this paper, the authors will consider two important ratios for quantifying the behavior of the charged particles in magnetic fields. The first ratio, R_g, is a geometric consideration that compares the Larmor (gyro-) radius, ρ_d, of the particle to the scale-size, L, of the experiment. For the dust particles to be considered as 'magnetized', this ratio should be much less than 1:

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

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, ω_{cd}, to the dust-neutral damping frequency, ν_{damp}. Here, the condition for magnetization requires that this ratio be greater than 1. R_c is equivalent to the inverse of the Hall parameter for the charged dust particles.

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

In the above equations, B is the magnetic field strength, 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_d is the thermal velocity of the charge microparticles, v_{tn} is the thermal velocity of the neutral gas atoms and δ is a numerical constant for the Epstein drag force which is ~1 to 2 [1]. Both equations (1) and (2) are dependent upon the charge-to-mass ratio of the charge microparticles and both equations show that small values of this ratio are detrimental to achieving magnetization.

If it is assumed that the charged microparticles are spherical, then the 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 [2]

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

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

It is noted that a complexity in this model arises from the fact that the dust grain surface potential, Φ_d, is a function of the properties of the surrounding plasma.

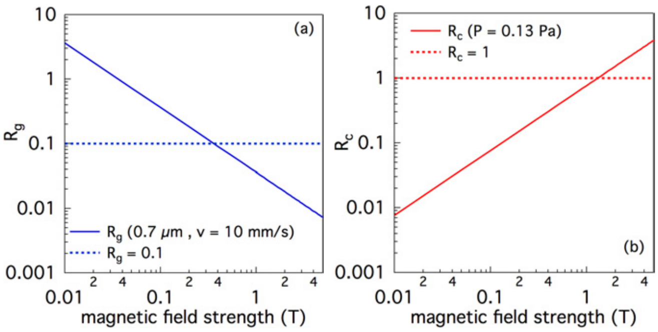

Figure 1. Plots of the scaling of the (*a*) geometric, R_g, and (*b*) collisional, R_c, ratios as a function of magnetic field strength for 0.7 μm diameter melamine dust particles.

When (1) and (2) are combined with the dust grain mass approximation and (3*a*) and (3*b*), the two ratios can be reduced to the scaling relations shown in (4):

$$R_g \sim \frac{a^2 v_d}{B} \ll 1 \qquad \text{and} \qquad R_c \sim \frac{B}{aP} > 1. \tag{4}$$

The scaling relations given in (4) show that in order to achieve the operational conditions necessary to achieve the magnetization, the ratio of magnetic field strength to dust particle radius, B/a, should be maximized. That is, experiments should be designed to operate with a combination of large magnetic field strengths and small particle size.

Figure 1 shows estimates of R_g and R_c for the typical experimental parameters listed in table 1. In figure 1(*a*), the geometric ratio R_g is computed assuming a 0.7 μm diameter, melamine particle with a velocity of 10 mm s^{-1} (i.e. this is approximately twice the thermal velocity of a particle near room temperature). The particle is assumed to be magnetized when its gyroradius is less than 1/10th the scale size of a vacuum chamber (here, $L = 17.5$ cm). In figure 1(*b*), the collisionality ratio R_c is computed using the same parameters as for figure 1(*a*) with the addition of an operating neutral pressure of $P = 0.13$ Pa. For these parameters, a magnetic field strength of $B \geqslant 1.3$ T is needed to satisfy both criteria simultaneously.

3. Previous experiments

The application of a magnetic field to dusty plasmas has been present since the earliest experiments. In the majority of these studies, the objective was not to create a fully magnetized dusty plasma (as defined above), but instead to modify the properties of the ions and electrons in the background plasma. Often, this is done to control the shape or volume of the plasma and in order to provide plasma conditions that are more conducive to trapping the microparticles. Additionally, the presence of the magnetic field can also indirectly affect the properties of a dusty plasma by altering the transport of ions and electrons in the plasma and, possibly, modifying how the microparticles become charged [3].

A number of current and past experiments have made use of a weak magnetic field to change the properties of the plasma. In particular, studies using the DPD [4, 5] at the University of Iowa, and the Matilda II experiment at Kiel University [6] have used weak magnetic fields of between 10 and 20 mT to control the properties of the plasma. In these studies, the magnetic field was not believed to have a direct impact on the microparticles; instead, the magnetic field expanded the region in the plasma where the microparticles could become trapped.

Beyond these studies, there have also been some experiments in which a magnetic field was used to indirectly influence the suspended particle cloud. This is the case in experiments by Nunomura *et al* [7] and Sato and co-workers [8–10] in Japan. In the Nunomura *et al* study, an axial magnetic field of $B = 87.5$ mT was applied to a dusty plasma in a low pressure ($p = 3.1 \times 10^{-4}$ Torr) electron cyclotron resonance microwave generated plasma. Here, it was observed that the entire cloud participated in global rotation apparently driven by the ion $\boldsymbol{E} \times \boldsymbol{B}$ drift. In the experimental observations reported by Sato *et al* magnetic field strengths up to $B = 1$ T, but at much higher neutral gas pressures of $p = 70$ to 220 mTorr were applied to a dc and rf-generated glow discharge plasmas. Similar to the experiments reported by Nunomura, the primary impact of the magnetic field was the observation of a global rotation of the dusty plasma cloud. It is noted that other groups have made similar observations including studies of: rotating dust clusters reported by Cheung *et al* [11] for magnetic field strengths up to 10 mT, rotating dust rings reported by Konopka *et al* [12] for magnetic field strengths up to 15 mT, rotating dust chains by Karasev *et al* [13] for magnetic field strengths up to 40 mT, and toroidally rotating dust structures in an anodic plasma by Pilch *et al* [14] for magnetic field strengths up to 60 mT.

In all of the aforementioned experiments, the magnetic field strength was sufficiently strong to influence the ions and electrons in the plasma. Then, through ion–dust interactions, there was an effect on behavior of the charge microparticles. However, as indicated in figures 1(*a*) and (*b*), for the correct combination of particle size and neutral pressures, magnetic field strengths in excess of 1 T are needed in order to achieve experimental conditions that are favorable for studying a fully magnetized dusty plasma. Reaching these types of conditions in a plasma are technically challenging in a research field that is generally characterized by small, 'table-top' scale experiments so there have only been a very few studies so far. The aforementioned work by Sato *et al* [8], the experimental device is capable of producing magnetic field strengths of up to 4 T, but their group indicated some difficulty at producing stable dc glow discharge plasmas under these conditions; thus, most of their work is reported for $B \leqslant 1$ T.

To the best of the authors' knowledge, there are two, currently active high magnetic field dusty plasma laboratories in operation today. The first laboratory has been operating at the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching, Germany, since approximately 2004 [15]. This system uses a pair of superconducting coils to produce a uniform magnetic field with a magnitude of up to $B \sim 4$ T with a warm bore of 40 cm. This device also has the ability to be rotated through 90° to allow the magnetic field to be oriented at an angle with respect to the direction of gravity. A small vacuum chamber (with a scale size $L \sim 20$ cm) is inserted

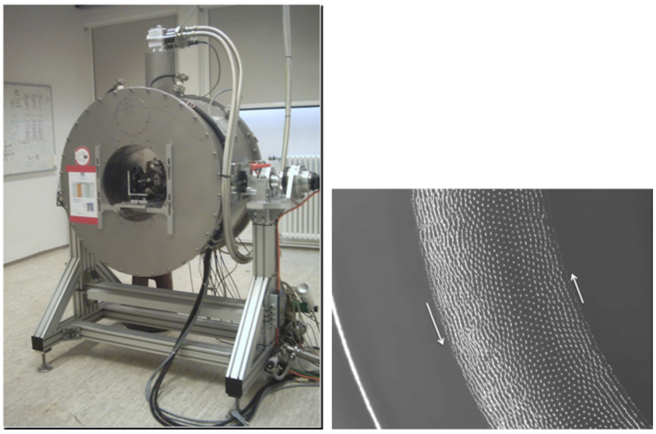

Figure 2. Left: photograph of the MDPX at the Max Planck Institute. Right: composite image of 10 video frames of a ring of particles that form in a horizontal plane; the magnetic field points out of the page and gravity points into the page. The two arrows show the direction of particle motion on each side of the ring, indicative of a sheared flow. (Images courtesy of U Konopka and P Bandyopadhay, Max Planck Institute for Extraterrestrial Physics).

into the magnetic field region and plasmas are produced primarily using a parallel plate rf discharge. Experiments in this device have focused on studies of particle cloud rotation, sheared particle flows and particle confinement in magnetic field strengths of $B \sim 1$ to 2 T [16]. Figure 2 shows a photograph of the MPE high magnetic field experiment on the left and a composite image of five video frames of particle motion is shown on the right. The composite image shows an example of a sheared flow in which the particles on the outer edge are moving in a counter-clockwise direction and particles on the inner edge are moving in a clockwise direction—as indicated by the arrows.

The second laboratory has been under development at Kiel University in Kiel, Germany, over the past several years. The Kiel laboratory now consists of three magnetic field experiments. The Matilda II [6, 14, 17] and Dustwheel [18] experiments are lower magnetic field devices ($B = 0.2$ T and 0.5 T, respectively) in which the ions and electrons are magnetized. Both of these devices have been used to study $\boldsymbol{E} \times \boldsymbol{B}$ flows in dusty plasmas. The newest experiment in the Kiel laboratory, Suleiman, is a uniform, high magnetic field ($B \geqslant 4$ T) experiment (figure 3). Suleiman uses superconducting coils, is rotatable, and has a warm bore of 30 cm. It is designed to contain a vacuum vessel up to 1 m in length. Suleiman began operations in 2011 and is currently being used to study the dynamics of dusty plasmas containing nanometer-sized particles [19]. In recently reported experiments, 100–200 nm diameter particles are grown, *in situ*, in the device leading to the production of several generations of nearly monodisperse, spherical particles. Dust density waves are frequently observed in particle clouds of the nanoparticle, although individual particles are difficult to observe. Upcoming experiments in the Suleiman device are expected to focus on gaining a better understanding of the forces that are acting upon the nanoparticles. One study of particular importance is whether the ion rotation caused by the magnetic field can induce a rotation in the neutral gas and whether this couples into the motion of the dust particles. Other areas of study will include mechanisms that lead to the confinement of the nanoparticle clouds and the development of new diagnostic systems for the detection of small particles.

4. The magnetized dusty plasma experiment

Using the lessons learned from the variety of experiments around the world, a new magnetized dusty plasma laboratory is presently under construction at Auburn University in Auburn, AL, in the United States and is scheduled to begin operations during the second half of 2013. The laboratory is centered on the MDPX device. The MDPX device is designed using superconducting coils with a target axial magnetic field, $B \geqslant 4$ T, a central warm bore with a 50 cm diameter, and the ability to rotate. However, it builds upon this core design used by the current generation of high magnetic field dusty plasma experiments.

First, MDPX has an 'open' design that allows, for the first time, direct radial access to the high magnetic field region. This enables considerably greater optical and diagnostic access to the plasma volume. Second, because of this open design, the MDPX device can accommodate a much larger vacuum chamber—and therefore, much larger plasma volume—than previous devices. The initial design of the MDPX device uses a 20 cm tall, 43 cm diameter, octagonally shaped vacuum vessel. This main chamber can be extended through the use of two, 15 cm diameter, cylindrical extensions. A schematic drawing of the MDPX device and photographs of the main octagonal chamber are shown in figure 4.

Third, MDPX uses four, independently programmable magnetic field coils. This allows the MDPX device to be operated in a variety of magnetic field configurations—from highly uniform modes similar to the MPE and Kiel configurations—to producing programmable linear gradients, to producing highly shaped cusp-like magnetic geometries. This will allow a much greater flexibility in the application of magnetic fields to dusty plasma studies. In particular, the ability to generate controlled magnetic field gradients—up to $1\,\mathrm{T\,m^{-1}}$—will create new opportunities to study the dynamics of dusty plasmas composed of ferromagnetic, paramagnetic and superparamagnetic particles. For example, a study performed by Samsonov *et al* demonstrated that the levitation and confinement of paramagnetic particles can be modified by a magnetic field gradient [20]. For the MDPX device, it may be possible to use mixtures of paramagnetic and non-paramagnetic particles to study new phase transition phenomena in dusty plasmas. Figure 5 shows examples of each of these magnetic configurations.

5. Discussion

The addition of magnetic fields to dusty/complex plasmas offers the possibility of an exciting new era to this area of research. The presence of the magnetic field will impact the dusty plasma at many levels. As the electrons, and then the ions, become magnetized, this will modify how the dust grains collect charge from the background plasma. This may have a

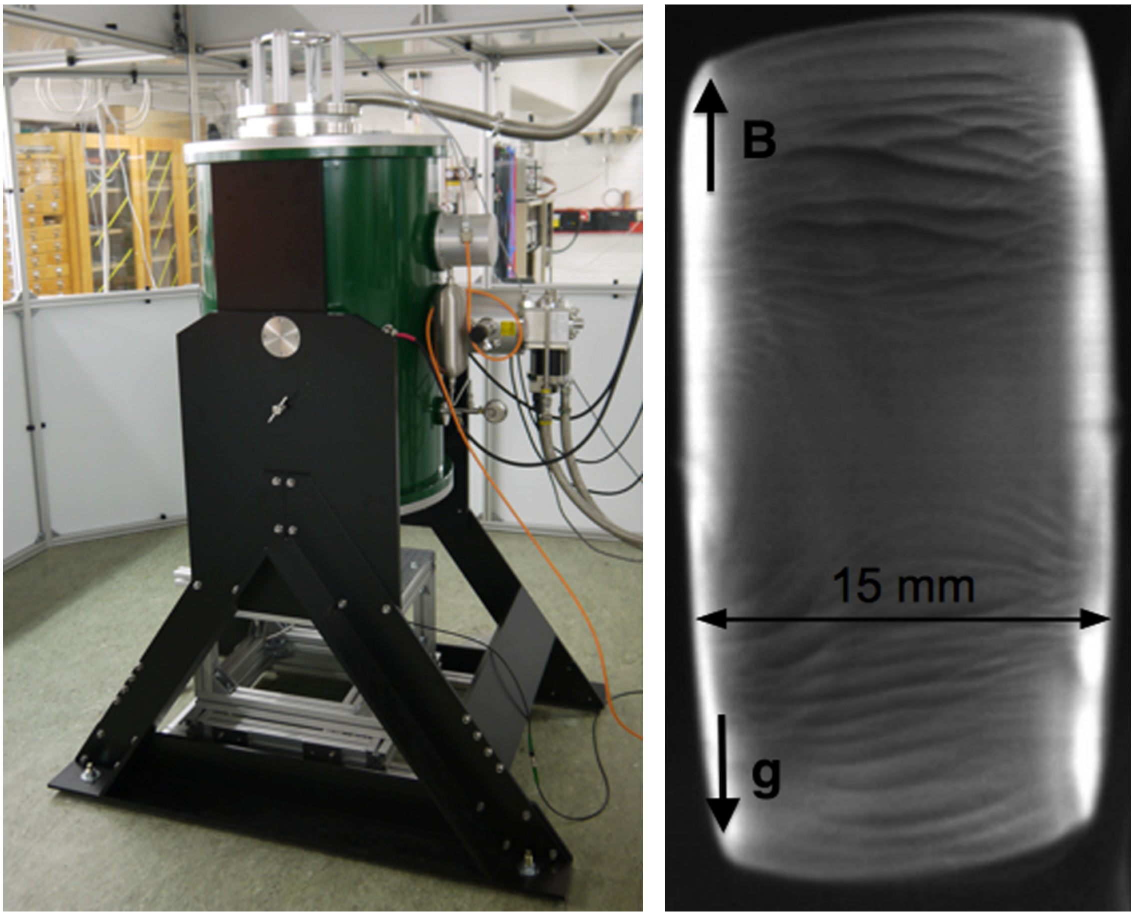

Figure 3. Left: photograph of the Suleiman experiment at Kiel University. Right: image of dust density waves in a particle cloud of 100–200 nm diameter nanoparticles. Here, the magnetic field direction is up and the direction of gravity is down as indicated by the arrows. (Images courtesy of F Greiner, Kiel University).

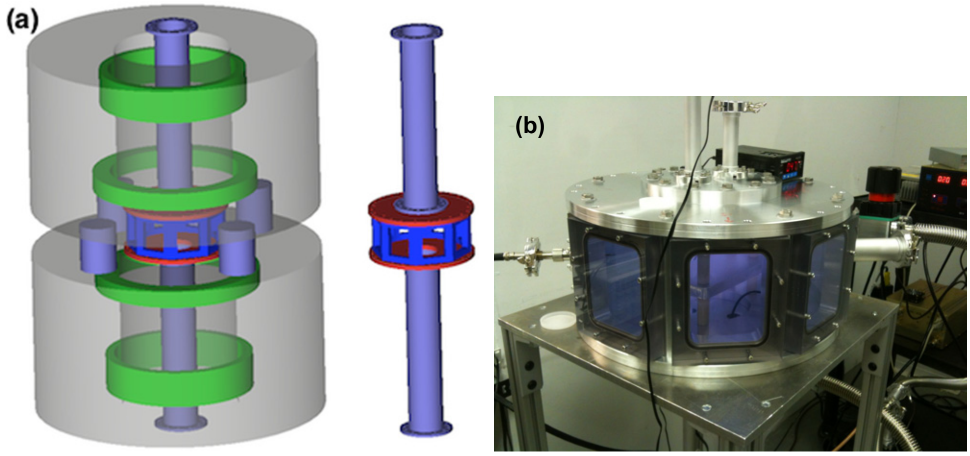

Figure 4. (*a*) Schematic drawing of the MDPX device. On the left is an assembly drawing of the complete device. The four superconducting magnet field coils are shown in green. The cryostat for the magnet system is shown in gray. The main vacuum vessel is shown inserted into the magnets and separately to the right. The main octagonal chamber is shown at the center with the two 15 cm diameter, 80 cm long cylindrical extensions. (*b*) Photograph of the main octagonal chamber on a test stand in the development laboratory at Auburn University. The blue color seen in the windows is from an rf-generated argon plasma.

significant impact on the equilibrium of the dust grain charge but, to date, no experiments have been performed to test this.

Beyond the impact on charge collection, it is also expected that the dust–dust interactions will be modified. This is because, in an unmagnetized plasma, Debye shielding is a spatially isotopic process, but this may not be the case for a strongly magnetized plasma. Here, with increasing magnetic fields strength, the motion of ions and electrons in the plane transverse to the magnetic field will become increasing restricted as compared with the direction parallel to the magnetic field. Quantifying this possible phenomenon will be another important area of study.

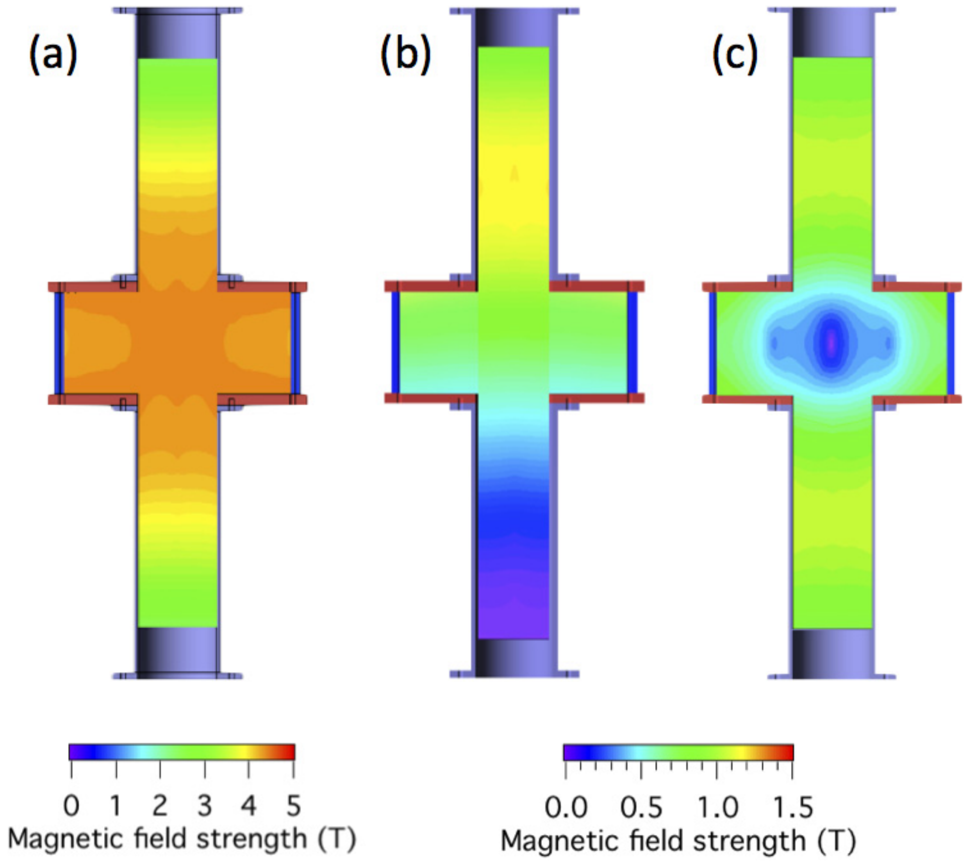

Figure 5. Models of the magnetic field configurations for the MDPX device projected onto the main octagonal vacuum chamber and a 40 cm long extension. (*a*) A uniform configuration with a magnetic field strength of greater than 4 T at the center of the main chamber. The color scale for the contours is shown directly below. (*b*) A linear magnetic field gradient (left) and a cusp magnetic field (right) configuration are shown.

A third important area of study will be determining stable regions of plasma operations to allow the dusty plasma phenomena to be investigated. As noted in section 3, Sato *et al* reported that stable plasma operations were difficult to achieve in dc glow discharge plasmas for magnetic field strengths above 1 T. In the rf discharge experiments performed at MPE and Kiel, under certain conditions, the plasma was observed to become filamented at magnetic field strengths above ∼2 T. Here, increasing the neutral pressure or increasing the spacing between the rf electrodes appeared to have a stabilizing effect of the filamentation. The development of stable operations regimes as well as new types of plasma sources and plasma diagnostics are critical for advancing the study of magnetized dusty plasmas.

Ultimately, the current generation and next generation of magnetized dusty plasma experiments are poised to make significant contributions to the field. Not only is there interest in achieving conditions where the dust particles are magnetized, but also the physics and engineering development of a steady-state, superconducting magnet, high magnetic field experiment is of general interest to the broader plasma physics community.

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