MRI: Acquisition of a stereoscopic particle image velocimetry system and particle transport diagnostics for dusty plasma investigations

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The presence of charged microparticles in plasmas is a subject with universal relevance. So called "dusty" or "complex" plasmas exist naturally in large astrophysical environments, such as nebula and planetary rings. Dusty plasmas also plays a role in industrial environments - such as the plasma aided manufacturing of microelectronics – where the presence of the dust can be a major source of contamination. Although the role of dust in astrophysical systems has been explored several decades, it has only been in the past dozen years or so in which these plasmas have been studied under controlled experimental conditions.

By definition, a dusty plasma is a usual ion-electron-neutral plasma in which a fourth component – the charged microparticles, i.e., the dust – are present. These microparticles can range in size from tens of nanometers to a few millimeters in diameter. These microparticles can become very highly charged with tens of thousands to millions of elementary charges. The presence of the dust can have a significant impact on the properties (density, charge distribution, etc.) of the surrounding plasma.

The dusty plasma experiments at Auburn are based in the Plasma Sciences Laboratory (PSL). The PSL is directed by PI of this proposal and supported through the NSF Faculty Early Career Development (CAREER) Program. Presently, the PSL has a unique niche in the dusty plasma community – the ability to perform real-time, two-dimensional particle transport investigations. This is possible through the use of a unique diagnostic tool in the field – particle image velocimetry (PIV). Within the worldwide dusty plasma community, the PSL is only laboratory that has the PIV diagnostic system. The availability of the PIV diagnostic allows the PSL to performed detailed measurements of particle transport and particle charging in dusty plasmas. This work has also led to the development of new techniques for non-invasive plasma potential reconstruction.

In addition to experiments at Auburn University, the PSL also has used PIV and other particle transport diagnostic techniques to perform collaborative studies at the Naval Research Laboratory (NRL) in Washington, DC and the Max Planck Institut für extraterrestrische Physik (MPE) in Garching, Germany. These collaborations were not only scientifically productive, but also provided valuable research training opportunities for Auburn undergraduate physics majors.

The key limitation of the present PIV diagnostic is that it is only measures two of the three possible velocity vector components of the microparticles. In the past 12 months, new commercial technologies have been developed to allow fully three-dimensional (i.e., stereoscopic) PIV measurements to be performed. This MRI proposal will be used to acquire a new, 3-D PIV system and will support the development of new particle transport diagnostic systems.

This MRI proposal seeks to keep the Auburn research effort in dusty plasmas at the forefront of this rapidly growing and evolving field. The Plasma Sciences Laboratory has made significant contributions to the understanding of particle transport in dusty plasmas by having the ability to perform unique and valuable measurements through its PIV diagnostic tools. Support of this MRI proposal will ensure that the PSL maintains its leadership in this field.

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1. Introduction

The presence of charged microparticles (i.e., dust) in plasmas is a subject with universal relevance. So-called "dusty" or "complex" plasmas exist naturally in large astrophysical environments, such as nebula and planetary rings.[1,2,3] The presence of the dust also plays an important role in industrial plasma applications systems, such as the plasma aided manufacturing of microelectronics.[4,5,6,7] Although the role of dust in astrophysical systems has been explored for several decades, it has only been in the past dozen years in which dusty plasmas have been studied under controlled experimental conditions.

For the past four years, primarily supported through a Faculty Early Career Development (CAREER) Program grant from the National Science Foundation, the Plasma Sciences Laboratory (PSL) at Auburn University has performed successful experiments on microparticle transport in laboratory dusty plasmas. The centerpiece of the laboratory is the particle image velocimetry (PIV) diagnostic tool that performs real-time, two-dimensional velocity reconstruction. The Plasma Sciences Laboratory is the only laboratory in the worldwide dusty plasma community that has the PIV diagnostic tool. The availability of this diagnostic system has allowed the PSL to take a leading role in the study of particle transport in dusty plasmas.

This Major Research Instrumentation proposal seeks to enhance the diagnostic capabilities of the PSL through the acquisition of a *three-dimensional* particle image velocimetry diagnostic and the development of pulsed laser transport diagnostic system. Support of this MRI proposal will greatly enhance the diagnostic capabilities of the PSL and provide new, highly detailed measurements of particle transport in dusty plasmas. Support of this proposal will also enhance our strong track record of undergraduate student research training and provide new opportunities to attract and train high quality graduate students. Furthermore, support of this proposal by the National Science Foundation ensures that the PSL maintains and expands its role as a leading laboratory for dusty plasma transport investigations.

This proposal is organized as follows. A brief description of the current state of dusty plasma investigations and a summary of experiments at Auburn University is presented. This is followed by a description of the physics of dust particle transport. The requested hardware is then described and a description of planned experiments at Auburn and with collaborators is given.

2. Dusty Plasma Research

By definition, a dusty plasma is a usual ion-electron-neutral plasma in which a fourth component, the charged microparticles, are present. These microparticles can range in size from tens of nanometers to a few millimeters in diameter. In laboratory plasmas, these microparticles can become very highly charged with tens of thousands to millions of elementary charges. The presence of the microparticles can have a significant impact on the bulk properties of the surrounding plasma. The dust is also responsible for introducing new classes of plasma behavior such as new collective modes and strongly-coupled phenomena.

2.1. Summary of recent dusty plasma studies

As dusty plasma experiments have progressed in the past dozen years, a variety of new plasma phenomena have been discovered. These include the identification of new dust-driven wave modes,[8,9] the modification of existing plasma instabilities,[10] the formation of strongly-coupled systems[11-16] – i.e., plasma crystals – and the identification of new types of behavior such as mach cone formation[17] and voids.[18-20] Furthermore, some very recent experiments – among them experiments performed by the PI of this proposal - are now using the dust particles as a diagnostic tool for the plasma. This next generation of experiments not only provides measurements of the microparticles in the plasma, but also allows the particles to provide detailed measurements of the underlying potential structure of the plasma.[21,22,23] Additionally, with ongoing studies[24] and newly proposed ideas [notably, the development of the International Microgravity Plasma Facility (IMPF) - a dedicated flight instrument on the International Space Station] for microgravity dusty plasma experiments, it is clear that in spite of the rapid growth of the field in the past five years, much work remains to be done.

Another aspect of dusty plasma investigations that is of interest is the differences in the properties of the suspended microparticles resulting from the plasma generation techniques. For example, in dc glow discharge dusty plasmas the suspended microparticles often exhibit a variety of wave modes and substantial internal transport. By contrast, in rf glow discharge plasmas the suspended microparticles often form strongly-coupled structures such as plasma crystals. The origin of these differences remains a topic for debate within the dusty plasma community.

In spite of the great progress that has been made in advancing the knowledge of dusty plasmas, the topic of particle transport remains relatively unexplored. After some initial investigations in the early 1990's,[25,26] much of the community became focused on the exciting discoveries of plasma crystals, in 1994[11] and dust driven collective modes, in 1995.[8] However, over the past three years, the work by the PI's group – through the development of new diagnostic approaches - has helped to generate a renewed interest in the area of dust particle transport.

The strength of this MRI proposal is that it takes advantage of the skills and experience that the Plasma Sciences Laboratory brings to the study of transport in dusty plasmas. Furthermore, as will be shown in Sec. 2.2, the new diagnostic tools to be acquired as part of this MRI proposal can be applied to virtually all types of dusty plasma experiments.

2.2. Dusty plasma studies at Auburn University

Dusty plasma experiments at Auburn University are performed in argon, dc glow discharge plasmas. Recent experiments produce microparticle clouds composed of 2.9 μm diameter silica particles. Dusty plasmas are generated at pressures ranging from 80 to 400 mTorr with a 300 to

500 V potential difference between the anode and cathode. The most distinguishable characteristics of the suspended microparticle clouds are: the very sharp cloud-plasma boundaries, the internal motion of the particles within those boundaries, and the presence of low frequency dust acoustic waves. An example of a typical microparticle cloud in the Auburn Dusty Plasma Experiment (DPX) is shown in Figure 1.

Through the support of the NSF CAREER program, the Plasma Sciences Laboratory acquired novel optical diagnostic tools that had not previously been applied to dusty plasma studies. The most important of these tools is the two-dimensional particle image velocimetry (2D-PIV) system.[27] With 2D-PIV, direct real-time, temporally and spatially resolved measurements of dust particle transport in the plasma can be made.

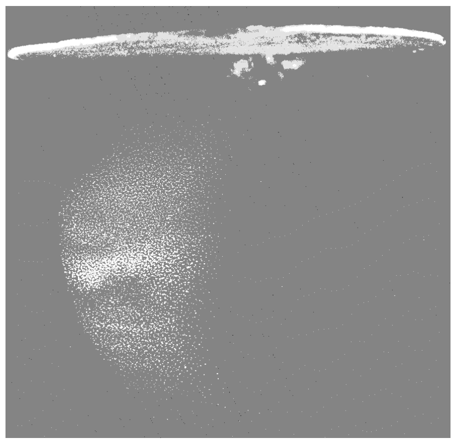

Figure 1: Photograph of dusty plasma in the DPX device suspended below the anode.

Transport studies performed by the Plasma Sciences Laboratory in dc glow discharge dusty plasmas have led to the identification of closed particle trajectories in dust clouds,[28] measurements of three-dimensional spatial structures in dusty plasmas,[29] and one of the first identifications of high speed particle flows in dusty plasmas.[30] Additionally, in a collaborative study with Prof. Robert Merlino of The University of Iowa, PIV techniques were used to identify boundary and possible non-linear effects in dust acoustic waves.[31]

In addition to studies at Auburn University, the Plasma Sciences Laboratory has established a number of very strong collaborations that expand the use of our unique diagnostic capabilities. During Summer, 2001, the PSL collaborated on experiments *both* at the Naval Research Laboratory (NRL) in Washington D.C. and Max Planck Institut für extraterrestrische Physik (MPE) in Garching, Germany.

In the NRL studies, the Auburn 2D-PIV system was sent to Washington for a seven week period to make measurements on the DUPLEX (NRL - DUsty PLasma EXperiment) device. These highly successful experiments have led to the first observations of new types of long-range transport phenomena in dusty plasmas.[32] An example of one of these measurements is shown in Figure 2. It is important to note that these studies were conducted primarily by Auburn University *undergraduate* students working in the NRL-DUPLEX laboratory.

Furthermore, this work was highlighted at the most recent American Physical Society – Division of Plasma Physics meeting in October, 2001; the cover photograph of the meeting Bulletin featured the joint Auburn – NRL experiment.

Simultaneously, at the MPE, experiments were performed using the Plasmakristall Experiment (PKE) hardware. The PKE is flight hardware that was flown on-board the International Space Station in March, 2001. Techniques have been developed at the MPE laboratories to simulate the effects of the microgravity environment in a ground-based experiment. A comparison of particle transport is made between flight measurements and ground-based studies.

A 2D-PIV system was developed using a combination of on-site hardware and the PIV software package INSIGHT[33] (provided by the PI). These measurements represented the first application of PIV techniques to rf glow discharge dusty plasmas. Specifically, these PIV measurements were used to characterize the formation of vortices at the edges of the dusty plasma and the transport of microparticles through voids. An example of one such PIV measurement is shown in Figure 3. In addition to the PIV techniques, a new transport measurement technique using strobed laser pulses was developed during the PI's recent sabbatical at MPE.

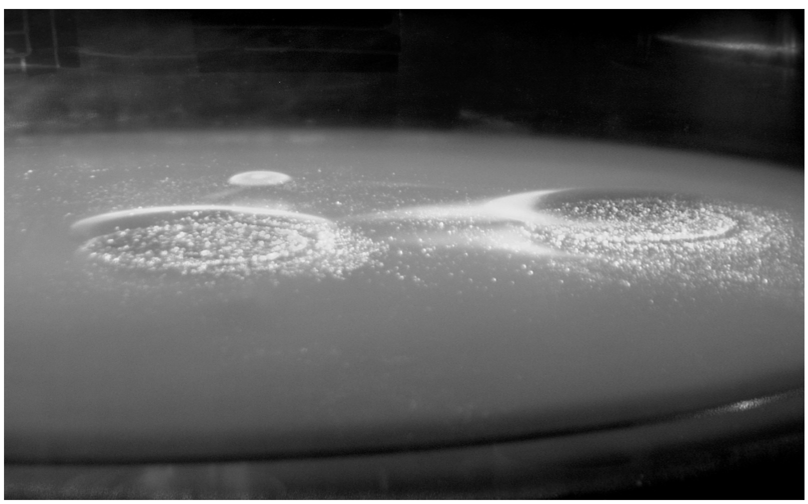

Figure 2: Long range dust particle transport in the NRL DUPLEX chamber. Shown are two 10 cm diameter piles of 1 μm diameter alumina particles are placed on a grounded, 80 cm diameter electrode. The uniform glow is from an argon dc glow discharge plasma. The light wispy objects in the foreground and the circular region in the background are microparticles suspended in the plasma. The particles are illuminated using the Auburn 2D-PIV laser system.

The aforementioned results provide evidence that the Plasma Sciences Laboratory has been scientifically productive. Specifically, since the acquisition of the 2D-PIV system in October, 1998, the PSL has produced six refereed journal articles with two additional accepted papers to be published in early 2002. The PSL has also delivered twelve dusty plasma related presentations at conferences and workshops and nine invited talks. Additionally, the first two papers based upon research results from Summer, 2001 have been submitted for publication and are presently being reviewed.

However, the PSL is not only a research laboratory but also a teaching laboratory. The PSL relies heavily on undergraduate students for assistance in research projects. Presently, five undergraduate students are employed by the PSL and a total of nine have worked in the laboratory since January, 2000. It is noted that for about one-half of the above presentations and for recently submitted papers, undergraduate students are listed as co-authors or, in the case of the presentations, are the primary authors. Furthermore, these presentations are made at major conferences (e.g., American Physical Society – Division of Plasma Physics), not at student conferences.

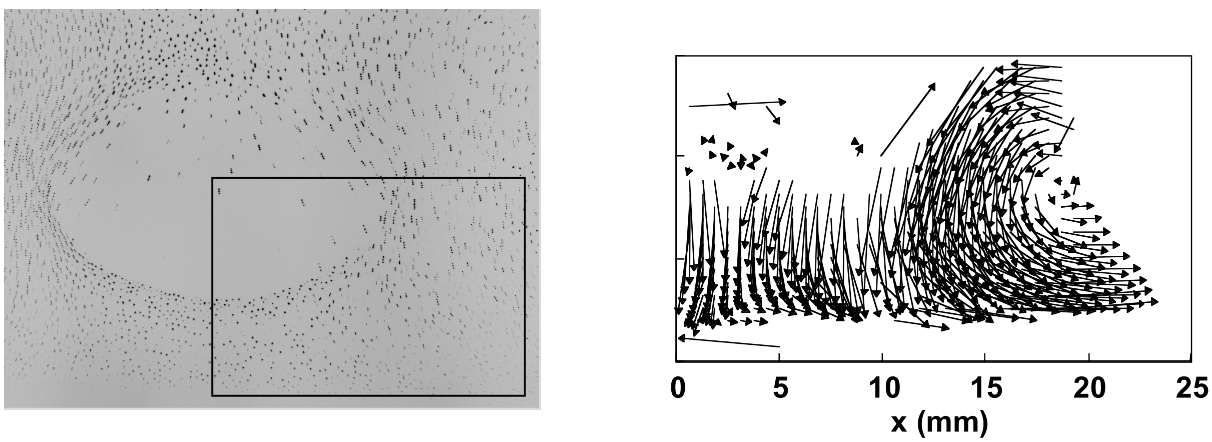

Figure 3: Particle transport in the PKE experiment. The figure of the left shows a void formed in the microparticle cloud. The box indicates the region of the image over which the PIV measurement is performed. The figure on the right is a PIV measurement from the lower right quadrant of the dust cloud. The vectors indicate the flow velocity of the microparticles in the cloud. A large vortex is observed at the lower right edge of the cloud. The reduced number of vectors in the upper left region is indicative of the fewer numbers of particles in the void region.

This strong track record of experimental results – both at Auburn and through collaborative studies – demonstrate that the Plasma Sciences Laboratory has made significant contributions to the dusty plasma community in the area of particle transport. The PSL possesses a truly unique diagnostic system and has had several years of experimental experience in this field. In addition to scientific contributions, the PSL has gained substantial stature in the dusty plasma community as shown by the fact that the PI of this proposal was selected to host the 10th Workshop on the Physics of Dusty Plasmas in June, 2003. Simultaneously, the PSL has a maintained strong commitment to scientific training by actively involving students in dusty plasma research. This combination of factors suggests that support of this MRI proposal by the NSF will satisfy the stated goals of the NSF to develop “people, ideas, and tools”.

2.3. Physics of dust particle transport

As discussed in Sec. 2.1, experimental investigations of dust particle transport have remained limited compared to other topics in dusty plasma research. One reason for this is, due to the fact that much of the early work in dusty plasmas were performed in rf glow discharge experiments. In these systems, the dust particles often form two- and three-dimensional strongly coupled arrangements – plasma crystals – in which the particles generally remain spatially fixed.[12-14] In experiments in which the surrounding plasma is formed using dc glow discharge[29,34] or thermionically heated filaments,[35,36] the microparticle behavior in the plasma is considerably more dynamic. Consequently, it has only been within the last two to three years that new experimental investigations of dust particle transport have been undertaken.

The microparticle transport is often described using the balance of forces that act upon the particles. For most laboratory experiments, these forces include: gravitational force (F_g), the electrostatic force (F_e), a neutral drag force (F_n) – based upon the Epstein drag formalism,[37] and an ion drag force (F_i). Forms for each of these forces are given in Eq. (1) below. It is noted that the ion drag term has two components – an ion collection term and an ion orbit term.[25]

Here, m_d, m_i, and m_e are the microparticle, ion, and electron masses, respectively; q_p is the charge of the microparticle, r_p is the radius of the microparticle, N is the neutral density, E is the local electric field, v_i is the ion velocity, v_d is the velocity of the microparticle, and v_n is the neutral velocity. The terms b_c and $b_{\pi/2}$ are impact parameters for the ion collection and ion orbit forces and Γ is the Coulomb logarithm integrated over the region b_c to the plasma electron Debye length. Final forms for these last three terms are shown in Ref. 25.

$$\sum \vec{F} = m\frac{d^2\vec{r}}{dt^2} = \vec{F}_g + \vec{F}_e + \vec{F}_n + \vec{F}_i \qquad (1)$$

$$where: \begin{cases} \vec{F}_g = m\vec{g} \\ \vec{F}_e = q\vec{E} \\ \vec{F}_n = -Nm_n\left(\pi r_p^2\right)v_n\vec{v}_d \\ \vec{F}_i = \begin{cases} \left|\vec{F}_{ic}\right| = n_i v_i^2 m_i\left(\pi b_c^2\right) \\ \left|\vec{F}_{io}\right| = n_i v_i^2 m_i\left(4\pi b_{\pi/2}^2\right)\Gamma \end{cases} \end{cases}$$

In addition to the balance of forces, the other required quantity needed to determine the dynamics of the microparticle in the plasma is the charge that resides on the surface of each microparticle. In a typical laboratory plasma, the microparticles become charged due to the flux of ions and electrons. In the simplest model, assuming warm electrons and cold ions and following orbit motion limited theory (OML) the ion and electron terms become:

$$I_e = 4\pi r_p^2 \left(\frac{en_e}{4}\right)\left(\frac{8kT_e}{\pi m_e}\right)^{1/2} \exp\left(\frac{eU}{kT_e}\right)$$
$$I_i = 4\pi r_p^2 \left(\frac{en_i}{4}\right)\left(\frac{8kT_i}{\pi m_i}\right)^{1/2} \left(1 - \frac{eU}{kT_i}\right) \qquad (2)$$

$$en_i = en_e - q_p n_p \qquad (3)$$

Where: n_p, n_i and n_e are the microparticle, ion and electron densities, T_i and T_e are the ion and electron temperatures, and U is the potential difference between the surface of the microparticle and the surrounding plasma. The microparticle charge is related to this potential via $q_p = 4\pi\varepsilon_0 r_p U$. It is noted that the first models of the particle transport in Barnes, *et. al.* (Ref. 25) did not include the effects of quasi-neutrality – Eq. (3). In subsequent studies by the PI of this proposal and other researchers,[38,39,40] this quasi-neutrality term is explicitly included in the modeling of particle transport.

The complexity of these equations arise from the fact that Eqns. (1), (2) and (3) are a coupled set of equations. That is, as the dust particles acquire charge from the plasma, this alters the local density and potential of the plasma. In turn, this alters the flux of ions and electrons to the microparticle. This implies that the microparticle charge is not a constant, but a dynamic quantity.

Thus, as the particle moves through the plasma, in a fully self-consistent model, there is a feedback between the microparticle charge and the local plasma conditions. Because of the highly coupled nature of this system, unfolding the mechanisms that govern the particle transport can be difficult to extract. The acquisition of the three-dimensional PIV will allow highly detailed temporally and spatially resolved measurements of the transport to be made.

The highly nonlinear nature of this problem has resulted in only a limited theoretical and computational effort to describe particle transport in dusty plasmas. Furthermore, as will be shown in Sec. 3, many of the transport phenomena observed in experiments suggest that detailed knowledge of the microparticle cloud – plasma boundary is essential to understanding the particle transport. Here, both detailed theory and experiments are required to explain the observed phenomena. With the addition of the three-dimensional PIV, it should be possible to obtain sufficient resolution to address phenomena at the cloud – plasma boundary.

If the microparticle charge can be determined independently, it is also possible to use the observed particle transport to diagnose the potential structure of the surrounding plasma. This is accomplished by computing the work done by the charged microparticles as they move from one region of a suspended cloud to another. This is equivalent to performing a line integral for each term in Eq. (1) over the distance traveled by the microparticle.

$$W_{total} = W_{gravity} + W_{electric} + W_{drag}$$

$$m_d aL = -m_d g(\Delta y) - q_d(\Delta\varphi) - \int_0^L \vec{F}_n \bullet d\vec{l} \quad (4)$$

$$\Rightarrow \Delta\varphi = -\left[\frac{m_d L(a + g\sin\theta) + \int_0^L \vec{F}_n \bullet d\vec{l}}{q_d}\right]$$

By solving for the electrostatic term, $W_{electric} = -q\,\Delta\varphi$, it is then possible to reconstruct the potential structure that the microparticle has experienced.[30] An extension of this is to introduce known perturbations to a microparticle cloud and use the subsequent streaming motion of the microparticles to "map" to spatial evolution of the potential structure.[21] This represents a significant advance in the development of dusty plasma diagnostics and allows new insights into the underlying physics of dusty plasma phenomena. Presently, it is extremely difficult, if not impossible, for most experiments to determine the potential structure in plasma that include the charged microparticles. The application of usual probe techniques introduces a significant perturbation to the suspended microparticles. Thus, the proposed 3D-PIV techniques represent a non-invasive method for obtaining information on potential structure that is resolved in both space and time.

Thus, one can consider the microparticle transport in a dusty plasma in two ways. First, one there is a need to explain the observed motion of the microparticles in the plasma. The dynamic motion of the particles within a cloud boundary as well as the apparent rigidity of the plasma – dust cloud interface hint at new properties for plasma confinement. Second, the motion of the individual microparticles through the plasma can be used as a diagnostic to measure the potential structure of the plasma. Consequently, the ability to measure the transport of charged microparticles in a plasma can not only provide valuable insight into the structure of a dusty plasma, but can also provide detailed information about the structure of the surrounding plasma.

3. Description of Particle Transport Diagnostics

The purpose of this MRI proposal is the acquisition and development of new microparticle transport diagnostics for dusty plasma studies. The Plasma Sciences Laboratory has worked to expand the understanding of particle transport in dusty plasmas through the use of novel optical diagnostic tools. Over the past three years, the PSL has developed the necessary expertise and experience to ensure that the proposed diagnostic tools will be successful. This section describes the operation of the current 2D-PIV diagnostic system and the operation of the proposed 3D-PIV system and pulsed laser transport diagnostic that are requested by this MRI proposal.

3.1. Two-Dimensional Particle Image Velocimetry

Particle image velocimetry (PIV) is the primary diagnostic approach used to measure the dust particle transport. It is first noted that PIV is not unique to the dusty plasma community. Rather, PIV was originally developed in the mechanical and aerospace engineering communities to study fluid, i.e., gas and liquid, flows around airframes and automobiles. However, the PSL was the first laboratory to adapt this technique to the study of dusty plasmas.[27]

In the PIV measurement technique, a pair of short, typically less than 100 ns, laser pulses are used to illuminate the particles. The laser beam is expanded into either a horizontally or vertically aligned sheet using a cylindrical lens. The two pulses are separated in time by a user-defined interval, 0.005 msec $< \Delta t_{sep} <$ 30 msec. A CCD camera is aligned perpendicularly to the laser sheet to capture the light scattered by the suspended microparticles. The firing of the laser pulses are synchronized to the frame grabbing rate of the CCD camera to ensure that each pulse appears on a single video frame. Using a cross-correlation technique, the displacement of particles between the two video frames is determined. Since the separation time between the two video images is known, a two-dimensional velocity field can be constructed in the plane of the laser sheet once a spatial calibration is performed.

Unlike the fluid measurements where PIV is used to "map" the flow in gases or liquids, in dusty plasma experiments, the velocity measurements represent the actual transport of the microparticles in the plasma. This is because the experimental configuration minimizes flows in the surrounding plasma and neutral gas environment. Nonetheless, considerable internal transport within the suspended microparticle clouds is observed. As noted in Sec. 2.2, the PSL now has considerable experience in performing and analyzing 2D-PIV measurements. This experience will be critical in applying these techniques to 3D-PIV.

3.2. Three-Dimensional Particle Image Velocimetry

While the 2D-PIV technique is, and will continue to be, an extremely valuable diagnostic tool, experimental measurements have shown some limitations to the technique. One limitation is that velocity vectors are reconstructed in the plane of illumination - hence the two-dimensional designation of the technique – thereby missing the third velocity vector component. An example of the need for this third component is shown in Figure 4.

Here, two measurements of the same dust cloud are shown. The cloud consists of two circular regions with a connecting band of microparticles flowing between the two regions, giving the cloud a dumbbell-like shape. The lasers illuminated a vertically oriented slice of the cloud denoted as the x-y plane. Different vertical slices are obtained by moving the lasers in the z-direction. The cloud is stable during these measurements with a fixed number of suspended microparticles. That is, no inflow or outflow of particles is observed.

However, the particle motion observed in different vertical slices can vary significantly. For example, in Fig. 4(a), there is a vortex-like structure. In Fig. 4(b), there is a strong upwelling of particles. In a system with a net conservation of particles and sharp, well-defined boundaries, the presence of such flow patterns clearly suggests that at the cloud boundaries, the particles must have a significant component of velocity in the third dimension.

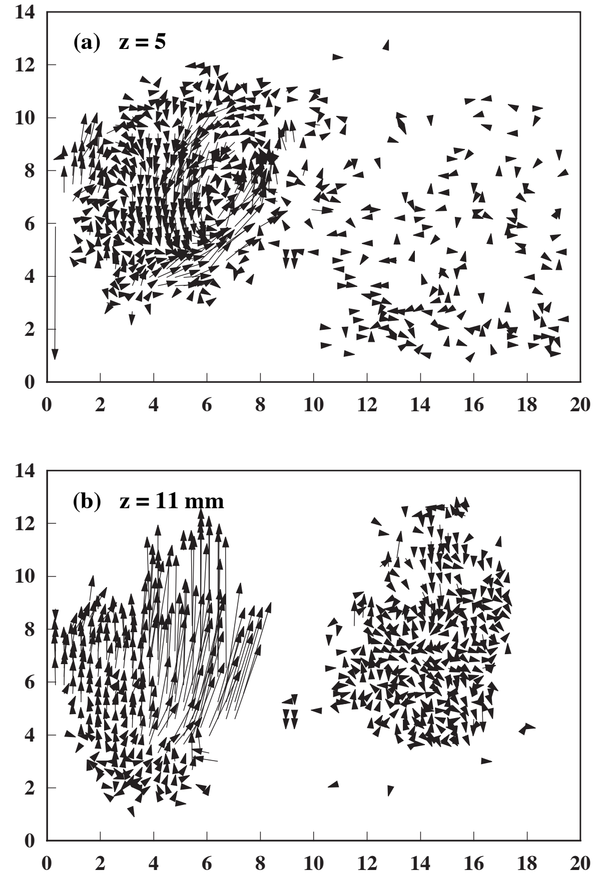

Figure 4: Comparison of particle transport in two different two-dimensional slices of a dust cloud. The horizontal and vertical axes are labeled in units of mm. (a) Measurement at z = 5 mm. (b) Measurement at z = 11 mm.

Therefore, one of the key advantages of a 3D-PIV system is the ability to reconstruct this third velocity vector component. This is accomplished using a similar approach as the 2D-PIV system. Here, the finite thickness of the laser light sheet is exploited. Two cameras are oriented to view the same illuminated region of space. Each camera captures a pair of images in the same fashion as the 2D-PIV system. However, through a calibration procedure, the two views are cross-correlated to remove the parallax between the two images. In this way, the third velocity component of the particles can be resolved. It is noted that sequences of slices would still be necessary in order to reconstruct the particle transport throughout the entire structure of the dust cloud. However, unlike the 2D system, there would be no ambiguity about the motion of the microparticles as they approached the cloud boundary. An additional benefit of the use of 3D-PIV is that with three-dimensional spatial and velocity information, it may be possible to construct full distribution functions for the particles in the cloud. With this information, questions such as evaluating the dust temperature and the development of fluid dusty plasma models can be addressed.

3.3. Pulsed Laser Transport Diagnostic

Both the 2D- and 3D-PIV techniques provide highly spatially resolved measurements. Furthermore, in constructing a single velocity vector field, there is also good time resolution. However, in constructing sequences of velocity profiles, the system is limited by the reset rate of the lasers and camera to ~ 100 msec. Thus, in order to observe faster changes in dusty plasmas (~ 10 msec) an alternate method must by employed.

One such technique, developed by the PI and his collaborators at MPE during Summer, 2001, is to use a modulated laser diode to illuminate the particles. Here, a diode laser is modulated using a square wave pulse sequence that has the laser on for 1 msec and off for 20 msec. Using a standard 30 frame per second (67 msec/frame) CCD camera, the particles appear as a series of 2 or 3 dots. An example of this is shown in Figure 5.

Using the NIH Image[41] image processing software package, 2D velocity profiles and acceleration profiles can be measured. It is proposed to duplicate this technique in the PSL as part of this MRI project. This will be used in conjunction with 2D- and 3-D PIV techniques to obtain a complete picture of particle transport in dusty plasmas.

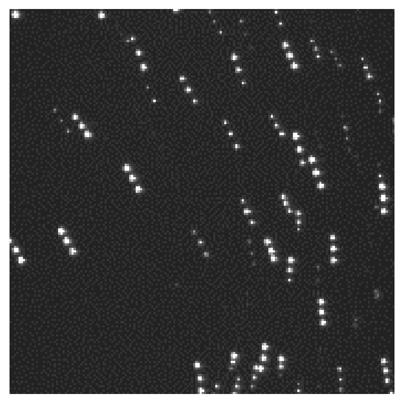

Figure 5: Measurement of particle transport in the PKE experiment using pulsed laser technique.

4. Requested Instrumentation

For this MRI proposal, two new optical diagnostics for microparticle transport studies in dusty plasmas will be acquired. The operation of both of these systems, the three-dimensional particle image velocimetry systems and pulsed laser transport system are described in Sec. 3. Here, the plans for acquiring, maintaining, and initial operation of these diagnostic systems are described.

4.1. 3-D PIV

The PSL has chosen TSI, Inc. to supply the 3D-PIV system. The Plasma Sciences Laboratory already has a good working relationship with TSI, Inc. as the present 2D-PIV system at Auburn University was purchased from TSI. Additionally, the TSI system interfaces with the existing 2D-PIV hardware and much of the software that has previously been developed within the PSL. An initial quote from TSI, Inc. for a full 3D-PIV system is $138,800. A copy of this quote is included in the Supplemental Documents for this proposal. This price includes lasers, cameras, computers and software.

The proposed system will provide a pair of frequency-doubled Nd:YAG lasers operating at 532 nm. The lasers are pulsed at 15 Hz and deliver an energy of 50 mJ/pulse at 20 – 30 ns/pulse. This is roughly twice the power of the existing 2-D PIV system. The light scattered by the microparticles will be captured using a pair of CCD camera, each with 2000 x 2000 pixel active areas (4 megapixels). This gives each camera four times the spatial resolution of the present 2D-PIV system which uses a1000 x 1000 pixel CCD camera. Coupled with faster computers, an improved Synchronizer (which controls the synchronization between the lasers, cameras, and frame grabbing hardware), the proposed 3D-PIV system will provide the PSL with a substantial performance upgrade over the existing 2D-PIV system.

It has been our experience that the PIV system is relatively low maintenance even at times with intensive use. Furthermore, from previous collaborative studies, the PIV hardware is reasonably portable and can be quickly disassembled and reassembled without significant difficulty. Initial experiments with the 3D-PIV system will take place at Auburn University. However, plans are in place to perform collaborative experiments with the Naval Research Laboratory (NRL, Washington, DC) using the 2D- and 3D-PIV approaches within the first 24 months after the acquisition of this hardware. Given the past success of collaborative investigations with the Naval Research Laboratory and the potential benefits of this new diagnostic approach, it is fully expected that these initial collaborations will serve as a model for the Plasma Sciences Laboratory to provide its diagnostic capabilities and expertise to the entire dusty plasma community.

4.2. Pulsed laser diagnostics

The pulsed laser diagnostic system will be assembled from fairly standard laser and optical components. It is planned to use a 30 to 50 milliWatt (mW) laser diode operating in either the red (~670 nm) or in the green (~532 nm). To assemble the system, the appropriate laser diode, power supply and support housing would be necessary – and there are dozens of companies that supply this hardware. For approximately $1,500 it is possible to assemble a 40 mW diode laser. The advantage of assembling the laser package internally is that when the diode fails (typically after 18 to 24 months of operation), it is relatively inexpensive, often below $100, to replace the diode chip. This is far less expensive than completely replacing a complete diode laser package (~ $1,000 for the desired power levels).

In addition to the diode laser, additional electronics for applying the modulation to the laser output will be necessary. This will include a TTL pulse generator and/or an arbitrary waveform generator. Hewlett-Packard/Agilent has an available 50 MHz programmable pulse generator (Model 81101A) that is well suited to this task. A lock-in amplifier will be used to synchronize external detection electronics to the laser pulses. A Stanford Research Systems SRS-830 has been identified as a instrument that satisfies the requirements of this diagnostic. Finally, some additional optics and optical accessories (e.g., cylindrical lenses, optical rails, optical posts, laser power meter, etc.) will be needed to generate the appropriate horizontal or vertical light sheet for illuminating the particles. The total estimated cost for this diagnostic system including the lasers, optics and detection electronics is $19,500. Like the PIV systems, it is believed that once this system is operational, it will be relatively easy to maintain.

4.3. Additional Components

In addition to the two laser diagnostic systems and associated components, several additional support components are included in this MRI proposal.

Optics and Optical Components: A new optical table is needed to mount the 3D-PIV and pulsed laser diagnostic systems. It is also planned to remount the Dusty Plasma Experiment on this optical table to ensure ease in alignment of the diagnostic systems. Newport, Inc. and Vere, Inc. have been identified as possible sources for the optical table. Additionally, it is planned to acquire a wavemeter from Burleigh, Inc. to monitor the output of the laser diode.

Computer Hardware and Software: The Plasma Sciences Laboratory is a computer intensive laboratory. Because most of the data acquired from the dusty plasma experiments is optical, i.e., in the form of image files, this places a significant demand on data archiving and data storage capabilities. With the addition of two other laser diagnostics, even greater demands will be placed on these capabilities.

It is planned to acquire an G4 class Apple Macintosh running the Mac OS X server software. A DVD-burner and a high volume (> 100 GB) RAID-based storage system will be added to this computer for enhanced data storage capabilities. A Pentium 4 class computer with a 30 frame per second, 1 Megapixel video capture card will be purchased for image capture from the pulsed laser diagnostic. Updated versions of LabView, the data acquisition software package, will be purchased from National Instruments for these computers.

Electronics: Additional plasma power supplies will also be purchased as part of this project. These new power supplies will provide improved stability to plasma operations. Sorensen, Inc. and Power Ten, Inc. are identified as sources for 1.5 to 3 kW (500 – 1000 V @ 3 – 5 A) for power supplies. It is also planned to purchase two high power (1 – 2 kW) bipolar operational amplifiers (BOP) from Kepco, Inc. These BOP's amplify signals from the pulse generators or arbitrary waveform generators to the other parts of the experiment.

Miscellaneous components: Finally, funds are requested to make improvements to the Dusty Plasma Experiment vacuum vessel. This will include increasing the size of viewports, improving the gas feed system, and improving pressure measurement tools.

4.4. Initial Operation

If funded by the NSF, the instrumentation requested in this proposal can be rapidly placed into operation. The pulsed laser system, which will be assembled from components, can be assembled and operational within 3 to 6 weeks. After the initial implementation at Auburn, the system will be tested at the Naval Research Laboratory on the DUPLEX device within 6 months.

For the 3D-PIV system, there is an approximately 8 to 10 week period before delivery and initial installation. From our experience with the 2D-PIV system, it will take roughly 3 to 6 months after installation to ensure stable and reproducible operation of the 3D-PIV system. After the first year of operation at Auburn, it is then planned to test the general applicability of the 3D-PIV approach through the collaboration with NRL.

5. Management of collaborative activities

As part of this proposed project, two collaborative studies will be performed within the first 18 to 24 months to evaluate the performance of the new diagnostic systems and their application to a variety of dusty plasma configurations. These collaborations are an extension of ongoing research activities in the Plasma Sciences Laboratory. These collaborative studies will be performed at Space Plasma Laboratory at the Naval Research Laboratory (NRL) in Washington, DC with Dr. William E. Amatucci.

At NRL, a new large volume (80 cm tall, 40 cm radius cylindrical vacuum vessel) dusty plasma experiment – DUPLEX (for DUsty PLasma EXperiment) – is operational. Here, collaborative studies will focus on explaining a variety of previously unidentified dusty plasma phenomena. Of particular interest to this proposed work is the identification of periodic, long range ($L > 10$ cm) transport of dust particles from one region of the DUPLEX plasma to another.[32] The application of the proposed 3D-PIV technique will provide the first spatially resolved measurements of this newly identified dusty plasma phenomenon.

To perform these collaborative studies, the PSL will use the duplicate the plans that led to the highly productive collaborations during Summer, 2001. Here, a four to six week period during the summer will be identified as an appropriate time to perform the collaborative studies. Experimental goals and plans will be established three to six months prior to the experiment. Several weeks prior to the start of the collaborative study, undergraduate and graduate students who are working on the Auburn dusty plasma projects will be given an intensive training on operating and maintaining the diagnostics independently. The PI and the students will then travel to the remote laboratory to setup the experiment. After the initial setup, the students will be left at the remote laboratory to complete the experimental studies. The PI, co-PI and students, will maintain daily contact with the students to ensure that the studies are successful. At the end of the collaborative study, the equipment and students will be returned to Auburn University.

As discussed in Sec. 2.2, this approach to collaborative studies has already proven to be a successful formula for the Plasma Sciences Laboratory and its collaborators. First, it makes advanced diagnostics for microparticle transport available to the dusty plasma community. And second, it provides an extremely valuable educational experience for Auburn University students. Demonstrating the capabilities of these proposed new particle transport diagnostic systems at NRL will most certainly strengthen our ongoing collaboration and will be certain to foster new collaborative studies.

6. Impact of proposed MRI project

This proposed MRI project has several potential benefits that will impact areas ranging from the physics of dust particle transport to the training of undergraduate student researchers.

First, support of this MRI proposal will provide additional NSF funding for an ongoing, successful CAREER project. Over the past three and one-half years, this project has demonstrated the use of 2D-PIV as a valuable diagnostic tool for the dusty plasma community. Support of this MRI proposal will represent a significant enhancement of the diagnostic capabilities of the Plasma Sciences Laboratory. Furthermore, it will significantly strengthen the growth of the Plasma Sciences Laboratory as a scientifically important laboratory within the dusty plasma community.

Second, the PSL already has a strong track record of student training in the area of dusty plasmas. As demonstrated in the past studies by the PSL (Sec. 2.3) and the proposed collaborative studies (Sec. 5), the PSL relies heavily on the participation of undergraduate and graduate students in research. At the PSL, while students are being trained, they are also considered to be valuable members of the experimental group. Students are strongly encouraged to attend conferences and to disseminate their research results in papers. Thus, support of this MRI proposal will ensure that Auburn students continue to have the ability to gain valuable scientific training using state-of-the-art facilities.

Third, this project has clear intellectual merit. At one level, the experiments to be performed using these new diagnostic systems will give new insight into the observed transport of microparticles in the plasma. Additionally, as shown in Sec. 2.4, it is now possible to use the measured particle transport to reconstruct information about the potential structure of the underlying plasma. Thus, the diagnostic systems that will be acquired and developed for this project will facilitate fundamental measurements in a new and rapidly evolving field of plasma physics. Furthermore, the PSL uniquely qualified to adapt these new instruments to dusty plasma transport investigations.

Fourth, the PSL has already demonstrated shared usage of particle transport diagnostic tools through collaborative investigations with the Max Planck Institute and the Naval Research Laboratory. Collaborations with the NRL are explicitly included as part of the acquisition of these new optical diagnostics. Once fully developed, these tools will strengthen these ongoing collaborations and help to foster new studies – notably in the realm of microgravity investigations.

In conclusion, the PI of this proposal firmly believes that the Plasma Sciences Laboratory has the skill, expertise, and experience to successfully incorporate these new diagnostic tools into the dusty plasma community. Support of this MRI proposal will allow the PSL to remain at the forefront dusty plasma transport investigations.