Studies of the physical and thermodynamic properties of dusty plasmas and plasma crystals

1. Introduction

Once dominated by fusion research, the plasma sciences have diversified and expanded tremendously over the past decade. In recent years, with the rapid growth of industrial applications of plasmas for materials processing and the increasing technological and economical importance of the interactions between spacecraft in near earth orbits and space plasmas, the importance of the plasma science has been realized. Nonetheless, plasma is an elusive form of matter and much experimental and theoretical work remains to be performed in order to fully understand the physics of plasmas.

1.1 Research component

Of particular interest to both the space plasma and industrial plasma communities is the interaction of particulate matter (~ 0.1 to 10 μm) with plasma. A plasma that is populated with particulate matter is commonly referred to as a “dusty” plasma. Dusty plasmas exist naturally in space and are believed to constitute much of the matter in planetary nebulae [1]. For industrial plasmas, especially in plasma processing applications, particulate matter produced as a by-product of the etching process can become suspended in the plasma [2-4]; this material can redeposit on the etched substrate once the plasma is discontinued causing the surface to become contaminated.

As a physical system, dusty plasmas provide an excellent tool for exploring the fundamental assumptions used in plasma physics [5-6]. Dusty plasmas represent a significant modification of the usual plasma approximation of quasi-neutrality. The dust particles, which are typically negatively charged by hundreds to thousands of electrons, are discrete point charges in an ion and electron background. This leads to regions of the plasma which can become severely depleted of negative charge and may lead to the formation of strong electric fields within the plasma. Numerous questions remain as to the treatment of the dust particles in modeling dusty plasmas, the effect of the dust particles in interpreting plasma phenomena, controlling the transport and confinement of dust particles in the plasma, and the formation of regular one-, two- and three-dimensional structures made of clusters of dust particles that are analogous to the crystal structures found in some solids.

The research component of this proposed CAREER project will use probe and optical diagnostic techniques, including the relatively new optical diagnostic procedure of particle image velocimetry (PIV), to measure the temporal and spatial behavior of particulate matter in a plasma. Specifically, the proposed studies will focus on:

(1) producing and controlling the transport of dust particles by using dynamic control of the plasma parameters via electrostatic traps, ion flow velocity, and plasma rotation;

(2) investigating the temporal and spatial evolution of the formation of "plasma crystals";

(3) using control of the plasma parameters to probe the physical (i.e., crystal dimension, lattice spacing, crystal structure) and thermodynamic properties (i.e., heat capacity, freezing and melting points, temperature, etc.) of the plasma crystals.

These studies are aimed at providing a more complete understanding of not only the behavior of particulate matter in plasmas, but also providing a better fundamental understanding of the plasma state of matter.

1.2 Educational component

Fisk University has a strong tradition of undergraduate student research, especially in the sciences. In the Physics Department, almost all of the approximately fifteen undergraduate students participate in research activities during the academic year and they have produced over two dozen scientific publications and presentations in the last two years. One of the problems facing physics departments nationwide, including the Physics Department at Fisk University, is a decline in the number of undergraduate physics majors [7-8] while there is a continued demand for well-trained physics majors. Concurrently, many teachers from local high schools who visit the research laboratories at Fisk note that they were unaware of the strength of Fisk's research program. The educational component of this proposed CAREER project will attempt to address both of these issues.

Each year, a team consisting of a high school physics instructor and one student from local high schools will be recruited to participate in a summer research experience at Fisk University. Each team that applies will also include a description of a small project to be assembled during the summer that can be used to demonstrate principles in the plasma sciences, electricity, magnetism, or optics (paralleling the themes of the dusty plasma research). The summer experience will consist of two components: (1) working part-time on the dusty plasma experiment; and, (2) developing the demonstration project. Moreover, during the following school year, the project PI will be available on a regular basis as a "science consultant" for the teacher and his/her school. In this role, the PI will make a commitment to give lectures at the school, help to develop additional demonstration tools, and serve as a mentor for students interested in the sciences. This will provide an opportunity to expose local students to the work done by professional researchers, create links between Fisk and local schools, increase the visibility of Fisk in the local community, and create a pipeline for students to enter the Physics Department at Fisk.

1.3 Physics research at Fisk University

Fisk University has a strong tradition of excellence in both research and education. Approximately 60% of Fisk undergraduates pursue advanced degrees even though Fisk University has an enrollment of approximately 850 students. As one of this nation's predominant HBCU's (Historically Black Colleges and Universities), Fisk prides itself on strongly encouraging the development of new knowledge through research.

Current research projects in the physical sciences at Fisk receive funding through NSF, NASA, FAA, DOE, ONR, U.S. Air Force, U.S. Army, and the EG&G Corporation. Also, Fisk University is one of fourteen universities in the country that is a designated NASA University Research Center - the Center for Photonic Materials and Devices (CPMD) operated through the Physics Department. In fact, the PI of this proposed research has received startup funding through the CPMD to develop the plasma laboratory facilities at Fisk. These initial facilities will be described in Section 3.1 of this proposal.

Support of this proposed research will greatly enhance the Plasma Sciences Laboratory at Fisk University. The topics to be explored as part of this research project will strengthen the growing links between the materials science and the plasma sciences at Fisk, further the dissemination of the plasma sciences, and add to the diversity of the plasma physics community.

2. Studies of dusty plasmas

Much of the initial studies of dusty plasmas has been focused on the accumulation of particulate matter (and consequently charge) on spacecraft. In particular, studies aimed at understanding this accumulation of dust particles would affect spacecraft performance and introduce perturbations to measurements [1, 9-10]. Since the mid-1990's, there has been a resurgence of interest in particulate matter in plasmas that has been driven by the industrial application of plasma technologies [2-3].

Plasmas have come into increasing use for the processing of semiconductors and microelectronic components because of the ability of the plasma to make well-defined, sub-micron etched structures on substrates. However, as the demand for smaller and smaller etched structures increases, it is necessary to maintain stricter control of the level of impurities in the plasma. As a result of the etching process, sub-micron sized material can become injected into the plasma. However, once the plasma is terminated, this particulate "dust" can redeposit on the processed surface. At a minimum, these dust particles contaminate the surface thus degrading the performance of the device. Thus, the technological and economical demands of plasma processing requires a more complete understanding of the interactions between plasmas and particulate matter.

2.1 Basic plasma studies

Electrical charge accumulation on the surface of an insulating particle is the basic mechanism for elevating the particle into the plasma. Assume that a spherical, macroscopic particle (grain) resides on a conducting surface exposed to a plasma. As charges pass through the sheath to the surface, they collect on the surface of the grain; in most experiments, due to the mobility of the electrons, the grain becomes negatively charged [4, 11]. Once the surface charge of the dust grain, Q_D, is large enough, the electric force, due to the sheath electric field, can exceed the combination of the gravitational ($m_D\mathbf{g}$) and the adhesive ($\mathbf{F}_{ad}$) forces that bind the grain to the surface [4, 11-12].

$$\mathbf{F}_E = Q_D\mathbf{E} \geq \mathbf{F}_{ad} + m\mathbf{g} \quad (1)$$

Once released from the surface, the dust particle is accelerated through the sheath and passes into the main plasma. The balance between the gravitational forces and local electric fields will then control the transport of individual dust particles in the plasma.

Once the dust particles enter the plasma, they can carry a large fraction of the negative charge of the plasma. As a result, the condition for quasi-neutrality of the plasma must be rewritten to include the effect of the dust particles.

$$en_i - en_e + \sum_k Q_{Dk} d(\mathbf{r} - \mathbf{r}_k) \approx 0 \quad (2)$$

In Equation 2, n_i is the ion density, n_e is the electron density, and the third term represents the sum of the charges carried by each of the dust particles in the plasma. In studying the basic physics of dusty plasmas, this third term carries very interesting implications. For regions of a dusty plasma in which there are few dust particles, there can be a large excess of positive charges. This may facilitate the formation of substantial electric fields within the plasma and has the potential to greatly alter the transport of particles in the plasma.

Numerous questions remain as to the role of ions in the transport and coalescence of dust particles in the plasma. Several models have been developed to address the perturbation of the potential profile in the wake of a dust particle [13-14]. It is believed that it is this positive wake potential may be responsible for much of the dynamics of the dust particles in the plasma.

Furthermore, the presence of the highly charged, massive (as compared to both ions and electrons) dust particles fundamentally alters one of the key conditions that defines the plasma state, quasi-neutrality. Consequently, dusty plasmas provide an excellent framework from which to pursue very basic plasma physics studies. These investigations include: perturbations to the conditions for quasi-neutrality, particle confinement and transport [12], and new plasma waves and instabilities that arise from the presence of the dust particles.

2.2 Dust acoustic waves

In addition to providing a tool for the exploration of basic plasma physics, there are physical phenomena associated with the presence of particulate matter in the plasma that can be examined. Two of the major topics under investigation in the study of dusty plasmas are dust acoustic waves (DAW) and plasma (or Coulomb) crystals.

Dust acoustic waves are low frequency waves in the plasma that are analogous to ion acoustic waves. They arise in the plasma due to the presence of the massive (relative to the ions and electrons) dust particles [10, 15-17]. Groups have reported observations of DAW's at frequencies as low as 10 - 15 Hz [12, 18-20]. However, some discrepancy remains as to the underlying physics that describes these waves.

To determine the relative importance of interparticle interactions (the coupling of the plasma), we consider the ratio of a particle's potential energy to its kinetic energy.

$$G = (q^2/4pe_0D)/(k_BT) \quad (3)$$

where: D is the interparticle spacing and k_B is Boltzmann's constant.

For most plasmas, G << 1 and the Coulomb interactions between individual particles can generally be ignored when attempting to determine the dynamics of the plasma; this is a case of weak coupling. However, for particulate matter suspended in the plasma, G >> 1 indicates strong coupling. Several studies have been undertaken to derive the DAW dispersion relationship using the strongly coupled regime of the fluid equations. In spite of some successes, there still exists disagreement as to the validity of this approach.

In addition to studies of DAW's, there is on-going theoretical and numerical studies of many other plasma waves and instabilities in dusty plasmas. These include investigations of Alfvén waves [21], solitons [16, 17], and electrostatic ion cyclotron instabilities [13] in dusty plasmas. Thus, it is clear that much work remains to be done in order to understand the physics of dusty plasmas.

2.3 Plasma crystals

Another unique phenomenon associated with dusty plasma is the ability of the dust particles to assemble (under the correct plasma conditions) into regular two- and three-dimensional structures. These structures form due to the mutual electrostatic repulsion of the highly negatively charged dust particles. These structures are called Coulomb crystals or plasma crystals. Experimental evidence suggests that these structures can form crystal-like structures similar to the body centered cubic (BCC) arrangement [22-24]. The truly exciting potential of these plasma crystal formations is the possibility to study solid state-like phenomena in a plasma environment.

To the best of out knowledge, a particularly interesting area that has not been widely investigated is the kinetics and thermodynamic of the plasma crystal. Specifically, studies of the phase transitions of the plasma crystal associated with changes in the plasma parameters have only recently been performed [24, 25]. In the studies by Quinn, *et. al.* [25], a two-dimensional model (Kosterlitz, Thouless, Halperin, Nelson, and Young, known as the KTHNY theory [26-30]) based on studies on colloidal matter, provides the framework for interpreting the 2-D structure of plasma crystals. In these studies, the results suggested that the plasma crystal was in a liquid-like phase, called hexatic, in which there can be long-range order but short-range disorder. Nonetheless, Quinn, *et. al.*, suggest that this result is inconclusive since the 2-D model used does not directly correspond to the physical system of the plasma crystal. Additionally, the experiment analyzed did not look at phase transitions, but rather looked at a static crystal to determine its phase.

It is clear that much more work remains to be done, both theoretically and experimentally, in order to determine physical principles that govern the formation and properties of the plasma crystals. Not only must experiments measure the static crystal structure, but must also have the ability to alter the plasma conditions and directly observe the changes in the plasma crystal.

In addition to studying the plasma properties of the plasma crystal, it is also possible to study the plasma crystal using techniques from solid state physics and materials science. For example, we may ask questions such as: What is the lattice parameter? What is the "temperature" of the crystal? At what temperature will the crystal "melt"? What are the latent heats of fusion and vaporization for the crystal? These pose very interesting physics questions that have yet to be answered. This proposed research project will attempt to address some of these issues.

3. Dusty plasma studies at Fisk University

The research component of this proposed CAREER project will be a study of the temporal and spatial transport of particulate matter in plasmas and the thermodynamic properties of plasma crystals. The research will encompass topics in plasma physics, electromagnetism, and optics. The experiment will be performed in two stages: (1) the creation of a dusty plasma and the characterization of transport phenomena in the plasma; and, (2) modifying the conditions in the dusty plasma, including the construction of a small electrostatic trap in the plasma device, to enable the formation of plasma crystals for study. Experiments will be performed on an existing plasma source at Fisk University, the Fisk Plasma Source (FPS). The proposed experimental program will be carried out over five years.

3.1 Fisk Plasma Source

A new plasma source has been built and become operational at Fisk University this summer (June, 1997). Support for the development of FPS has been through startup funds provided the by Physics Department and by equipment provided by the NASA-Fisk University Center for Photonic Materials and Devices (CPMD) and the Physics Department.

The major component of the FPS is a 6-way stainless steel cross vacuum vessel. This vacuum vessel was previously used as part of a plasma thruster experiment. The PI has spent much of his recent effort making modifications to the vacuum vessel to convert it into a useful plasma experiment. The vacuum vessel has a large volume; it has a 10" inner diameter with 13.5" flanges and an overall length of ~24" along each axis. The large volume combined with the low pumping speed of the available vacuum system limits the neutral pressure in the FPS to a minimum of 10 mTorr. A schematic of the FPS device is shown in Figure 1.

Plasmas are generated in FPS primarily through the use of thermionically emitting tungsten filaments or DC glow discharge. Argon gas is introduced into the vacuum vessel to raise the neutral pressure to 100 to 300 mTorr. A plasma is formed as the electrons ionize the neutral gas. Both of these plasma generation configurations have been used successfully in dusty plasma experiments [12, 20]. We have also modified a conventional microwave oven by extracting the magnetron for use in electron cyclotron resonance heating (ECRH) of the plasma. However, the high neutral pressure, and consequently high collisionallity and neutral particle interactions, may limit the ECRH plasma operations of the source.

To aid in the confinement of the plasma, two electromagnets are wound directly onto the vacuum vessel walls to produce a mirror magnetic field with a peak field strength ~150 Gauss within the vacuum vessel. We have also developed a model of the magnetic structure in the FPS device. For this model, parts of the Integrable Field Torsatron (IFT) code at Auburn University [31, 32] were modified to model the magnetic fields of linear plasma devices. This modified code, has been further upgraded by the PI of this grant to include single particle trajectories and will later be modified to include Monte Carlo modeling. The current version of the code (Linear Device Code - LDC) has been used to model the magnetic structure in the FPS. A three-dimensional contour plot of the magnetic field strength as a function of the axial and radial position in FPS, as predicted by the code, is shown in Figure 2.

Measurements of plasma parameters on the FPS are made using a Langmuir probe and by optical emission spectroscopy. Measurements of the plasma emission spectra are made using a Zeiss CCD spectrometer. One of the first emission spectra made of an FPS plasma is shown in Figure 3. While the resolution of the spectrometer was too low in this case to obtain information about the ion temperature and density, the peaks in the spectra did allow us to identify several atomic species in the plasma. Not surprisingly, due to the relatively high base pressure in the vacuum vessel, many of the observed lines were due to the residual constituents of air. At the time of this writing, Langmuir probe measurements of the plasma density and temperature profiles are on-going. We have successfully carried out preliminary experiments that have demonstrated that dusty plasmas can be created in the Fisk Plasma Source.

3.2 Dusty plasma transport studies

During the first year, a major upgrade of the vacuum vessel will take place. The primary focus will be to improve the vacuum conditions to achieve base pressures in the 10^{-5} to 10^{-6} Torr range. This will be accomplished by the addition of high speed (> 2000 liters/sec) diffusion and roughing pumps. After the upgrade, which is expected to take only 3 to 5 months, the scientific investigations will focus on the transport properties of particulate matter in plasmas.

In the first year, the transport studies will make use of the Mie scattering of laser light from particles suspended in the plasma [12, 21-22]. A microscope system, attached to a CCD camera will record the scattered He-Ne laser light. The first year studies will confirm that the upgraded FPS can produce high quality dusty plasmas and then perform an initial study of the behavior of the dust particles in the plasma. Using image techniques similar to those shown in Refs. 12, 21, and 22, it will be possible to look at the trajectories of the dust particles as they leave the sheath and enter the plasma. The experimental results will be compared against the theoretical models of dust particle transport developed by Sheridan and Goree [11] (refer to Section 2.1) and later modified by authors of Ref. 12.

The limitation to both forms of the dust particle transport model is that it assumes a generally one-dimensional motion to the particles as they leave the surface and pass through the sheath to the plasma. The experimental observations made by Prabhakara and Tanna [12] show that, once suspended in the plasma, the dust particles execute parabolic (i.e., at least 2-dimensional) motion. The current models do not yet include a full description of the passage of the dust particles through the sheath. Thus, the transport studies in this proposal will focus on developing a more complete description of how the dust particles enter the plasma.

3.3 Particle image velocimetry studies

The previous section described the first year of the dust particle transport studies. In the second year of the dust particle transport studies, a relatively new technique will be used to make both temporal and spatial measurements of the transport of dust particles in the plasma. This technique, particle image velocimetry (PIV), has been successfully developed over the past seven to ten years as a powerful technique for investigating fluid systems [33-34].

For fluid experiments, small spherical target particles (typically 1 to 10 μm in diameter), are placed in a flowing liquid. *Two* laser pulses, in the form of a sheet of laser light, are fired into the liquid. The reflected light from each 5 to 10 ns pulse is recorded. Each image of the reflected light is digitized and analyzed by a computer. Software has been developed to simultaneously analyze both images and to create a mapping of the particle motion from the first image to the second. In this manner, a vector flow field of the fluid can be obtained.

I suggest that this technique is an ideal diagnostic tool and propose its use in analyzing dusty plasmas. To the best of our knowledge, PIV has not been previously used to study a dusty plasma. The primary difference between the fluid mechanics experiment and the dusty plasma experiment is that the vector flow field produced by PIV will give a *direct* measurement of both the location and the velocity (i.e., the transport) of the dust particles. Thus, this diagnostic technique should provide a unique insight into the transport mechanisms of dust particles in the plasma.

Because of the increasing use of this PIV technique to analyze fluid systems, a number of companies now have very economical PIV laser systems for sale. The PI has identified a 180 mW Nd-YAG solid state laser system, specifically designed for PIV studies from Continuum Corporation [35]. This laser would produce two 5 ns (nominal) laser pulses at 532 nm separated by up to 50 msec at a repetition rate of 15 Hz. Additionally, software is available from TSI Corp. that is specifically designed to analyze PIV data from images obtained using a CCD camera [36].

3.4 Plasma crystal studies

In addition to studies of the transport of dust particles in the plasma, this proposed research project will also investigate the collective behavior of dust particles in the plasma; i.e., studies of plasma crystals. Two electrodes will be placed in the plasma, biased negatively, to form an electrostatic trap for the dust particles. Most studies of plasma crystals suggest that this proposed configuration is successful for making observations of the properties of plasma crystals.

With the two available laser diagnostic systems, especially the PIV system, we expect to directly observe the formation of the plasma crystal lattice both spatially and temporally. The initial experiments will use the PIV diagnostic system to provide a unique insight into the physical processes that cause the dust particles to coalesce in the plasma and to form the observed 2-D and 3-D structures. The He-Ne laser/camera system will be used to measure the structure of the formed crystal.

After an initial series of experiments to confirm the formation of the plasma crystals, the emphasis of the experimental studies will be to characterize the plasma crystal using analogous concepts borrowed from solid state physics and materials sciences. One of the first questions to be answered is to determine the lattice dimension and crystallographic orientation of the "grown" plasma crystal. Peiper, *et. al.* [22] have shown that the scattered laser light from the plasma crystal is adequate for making these measurements.

As shown in Section 2.3, studies of the thermodynamic properties of plasma crystals are still in their infancy. Most studies to date have examined the state properties of a "static" crystal. In the studies performed as part of this research proposal, the laser diagnostic system will provide information on the response of the plasma crystal to changes in the plasma parameters. A series of experiments will make perturbations to the plasma density (by changing the amount of gas in the chamber), heating current and bias voltage of the filament, and plasma temperature (through the use of a RF power source to be purchased in the third year of this grant). It is expected that changes in the plasma parameters will make perturbations to the plasma crystal that may be manifested in the lattice dimension of the crystal, or in the orientation of the crystal.

By investigating the properties of plasma crystals during periods when the surrounding plasma is being perturbed, it may be possible to directly observe phenomena such as phase transitions in the plasma crystals. From these observations, it will be possible to infer quantities such as the latent heats of fusion and vaporization. The ultimate goal will be to develop a state function for the thermodynamic state of the plasma crystal; i.e., $Y = Y(n_i, n_e, T_i, T_e, \text{etc.})$, where Y, is the label for the thermodynamic state of the plasma crystal.

3.5 Applications of dusty plasma phenomena

During the first three to four years of this CAREER project, much of the emphasis of the research component will focus on understanding the physics of the transport of particulate matter in plasmas and the properties of plasma crystals. However, the study of dusty plasma extends beyond the realm of fundamental science. As discussed at the beginning of Section 2, particulate matter produced during plasma processing can become trapped in the plasma and later, upon terminating the plasma discharge, this material can redeposit on the processed target. As plasma processing technologies develop techniques to produce sub-micron etched structures on semiconductor targets, the control of particulate matter suspended in the plasma will become an increasing important task.

During the fourth and fifth years of this project, we will consider techniques for controlling the transport of the dust particles and develop tools to manipulate the spatial distribution of dust particles in the plasma. Preliminary concepts that have been considered by the PI involve the use of focused "sheets" of electrons. With the proper alignment, it may be possible to fire an electron beam sheet between the layers of a plasma crystal. The repulsion between the electrons in the beam sheet and the negatively charged dust particles can cause the plasma crystal to be "cleaved". A schematic of this approach is shown in Figure 4.

A variation of this technique may also provide a means to remove the dust particles from the plasma. For example, an electron beam could be fired into the plasma to "sweep" the plasma clean of the negatively charged dust particles. In a plasma processing system, this cleaning beam would be fired just prior to turning off the plasma discharge, thus removing possible contaminants. However, numerous theoretical and technical challenges such as, the transport of the dust particles in the presence of the electron beam, charge buildup on the processed material, development of the optics to control the electron beam, and development of a long-life, low cost electron emitter, would need to be addressed. Nonetheless, the fundamental physics research on the transport properties of dusty plasma performed in the first years of this proposed project is essential to develop applications that can control the behavior of particulate matter in plasmas.

4. Educational outreach activities at Fisk University

Fisk University has a long and impressive tradition of educational excellence. For the past five years, Fisk has been named among the top 100 “Best Buys” by Money Magazine [37]. Fisk is also proud of the fact that in proportion to its size, it graduates a larger number of African-American students who achieve the Ph.D. than any other university in the United States. Thus it is clear that at the University-wide level, we have a strong record of student training.

Specifically, in the Physics Department, through the CPMD, our training record is excellent. As discussed in Section 1.3, many of our students have made scientific presentations at both professional and student conferences and almost all of our majors, who are beyond the sophomore year, participate in some research activity and also receive substantial financial support from the department. We believe that the more than twenty Ph.D. faculty and researchers provide a strong support structure for our students.

However, as has been recently documented in *Physics Today*, the population of incoming freshman physics majors has begun to decline [7-8]. Thus, in spite of our track record of student training, if we fail to attract and recruit talented students to physics, all of our training activities will be rendered useless. Therefore, the educational activity in this proposed CAREER project will be primarily focused on outreach activities that bring high school students and teachers into contact with modern plasma sciences research.

4.1 Training Goals

Because of Fisk University’s strong research and educational record, we have the opportunity to offer a unique training experience to both the high school student and teachers; most especially to students and teachers from traditionally under-represented minorities in the sciences. The proposed educational program will specifically focus on local high school physics teachers and their students. The program has three primary goals:

(1) To expose high school juniors from the Metropolitan Nashville area to the activities in the Fisk University Physics Department with the aim of fostering their interest in the natural sciences, with a specific emphasis on physics.

(2) To provide technical and direct hardware support to local high school physics teachers.

(3) To establish long-term contacts with the faculty at local high schools and to expose the teachers to the unique opportunities available for their students at Fisk.

In order to achieve these goals, a competitive summer training program for **both** a high school physics teacher and a student will be established as part of the existing summer research programs that are offered through the Physics Department. The six week summer training program will allow both the student and the teacher to interact with not only the PI, but also with the other Physics Department faculty. In this way, both the student and the teacher will have a very good opportunity to assess the capabilities of the Physics Department at Fisk.

In addition to exposure to the entire department, the teacher and student will carry out a two part summer research activity based in the areas of electricity, magnetism, and optics which are the main thrusts of the research component of this grant. For one part of their research, they will take and analyze experimental data from the dusty plasma experiment on FPS. The second component of their research will be to develop a demonstration experiment for use in the physics classroom. At the end of the summer, the completed demonstration project would be turned over to the high school. Therefore, not only will the student and teacher get some exposure to modern scientific research, but they will also have the opportunity to develop a tangible project that can be used in the classroom.

The responsibility of the PI is to ensure that the experiences of the teacher and student are positive. This program gives Fisk an excellent opportunity to enhance the visibility of its research activities in the local community. By including both the high school teacher and the student, we have the opportunity to expose all of the students in the teacher's classes to these experiences. To reinforce these experiences, the PI will also serve as a "science consultant" to the high school physics class throughout the academic year. In this manner, the PI believes it will be possible to achieve all of the goals of the educational program.

4.2 Summer program activities

For the past six years, the Physics Department at Fisk University has been supporting an undergraduate summer research program (SRP). Originally supported through a NSF/REU grant, this program is currently supported through the CPMD, NSF/RIMI, and NSF-supported Alliance for Minority Participation (AMP) grants. Over 70 undergraduate students from across the United States have participated in this summer program. This year (Summer, 1997), the PI of this CAREER proposal is serving as director of the SRP.

The summer program activities for the student/teacher team will be incorporated into the existing SRP. In order to prevent overload, the Physics Department has agreed to reduce, by two, the number of undergraduate SRP students that will be assigned to the PI's research group.

The specific activities related to the summer program begins in mid-March when an application package would be sent to the local high schools. The package will invite joint applications from a high school junior and high school teacher to participate in a 6-week summer research activity at Fisk University. It will further request that the student/teacher team develop a small demonstration project, based in the plasma sciences, electricity, magnetism, or optics, that could be completed during the summer. Such a demonstration project complements the focus of the PI's research activities.

The motivation behind the demonstration project is to allow each pair to have a well-defined goal for their summer activities. Further, by allowing the participants to propose and develop their own project, they can more effectively address the needs of their school's programs. While it is not expected that the proposed summer projects will be "original scientific research", it is expected that the student/teacher team will develop a project that addresses a specific need of their school. The role of the PI will be to provide guidance and technical expertise while relating the relevance of the demonstration project to research in the Plasma Sciences Laboratory.

The winning team would be selected based upon the student's academic achievements and potential, the teacher's experience, and the relevance of their proposed project. The team that is selected would receive a development budget of $2,500 to implement their project during the summer. Additionally, the student and the teacher will each receive a stipend. The teacher will receive $4,000 for the summer and the student will receive $1,500.

During the summer, from mid-June through the end of July, the student/teacher pair would work in the Plasma Sciences Laboratory. Their work would be integrated into the other summer programs at Fisk. As such, they will be expected to make regular presentations about the progress of their work. They would spend about one-third of their time learning about plasmas and the optical diagnostic and probe techniques used in the dusty plasma experiments. They will also participate taking experimental data and learning how to analyze and interpret that data. The remainder of their time would be focused on developing their demonstration project. Additionally, the teacher would be given training on writing grants and proposal to expand the research project from a demonstration to a full classroom laboratory project. At the end of the summer, the completed project will be given to the high school.

4.3 Academic year activities

A major goal of the educational component of this proposed CAREER project is to establish long-term relationships with the faculty at local high schools. To achieve this goal, during the academic year the PI will serve as a science consultant for the high school physics teacher and for the high school. This activity is aimed at forming a bridge between the high school and the university.

Specific activities include regular quarterly contacts between the PI and the teacher in his/her classroom. These exchanges will include in-class demonstrations, tours of the PI's laboratory facilities and other laboratory facilities at Fisk University, and providing both technical support for the teacher's class and mentoring for students interested in physics. In particular, during the visits to the teacher's class, the PI will form links between the topics under discussion in the physics class and the research activities in the laboratory. These regular contacts will also allow students in the high school physics class to interact with professionals in the scientific community. Most importantly, this will aid in demystifying the role of science and the activities of scientists.

A potential benefit of this long-term contact will be an exchange of ideas between the high school physics faculty and university physics instructors. This may lead to a better understanding, on both sides, of the preparation level of students entering college. Hopefully, this will establish a mechanism for improving both the high school and college physics curricula.

4.4 Educational program assessment

To assess the educational component of this CAREER proposal, the student and high school teacher participants will be given a questionnaire at the end of the summer. This questionnaire will ask the participants to rate the summer program activities and to make suggestions for improvements. Additionally, twice during the academic year program, separate surveys of the students and teachers will also be used to evaluate the educational program. Results of these surveys will be reviewed jointly by the PI and the Physics Department chair and the program activities will be adjusted to better serve both the high school students and the high school physics teacher. The program will be successful if regular contacts between selected high schools and the Physics Department are maintained beyond the year-long educational activities.

4.5 Other educational activities

In addition to the program directly aimed at high school students and teachers, this CAREER proposal will also provide support for undergraduate students to participate in research in the Plasma Sciences Laboratory. As the instructor of the University Physics course (a calculus-based introductory physics course - PHYS 131/132), the PI will be in a unique position to identify academically talented students and recruit them to perform plasma physics research. During the first two years of this grant, one undergraduate student will be supported for both the academic year and the summer. During the remaining three years, two undergraduate students will be supported each year. Additionally, at least one graduate student will perform research related to this proposal. The Physics Department and the CPMD have agreed to provide support for graduate students who participate in this project.

5. Relationship of proposed project to career development

This proposed CAREER project will have a significant impact on the career development of the PI. The research component of this proposed project will allow the PI the opportunity to make a substantial contribution to the field of plasma physics. The research project addresses issues of both a fundamental nature, e.g., the physics of the transport of particulate matter in plasmas, and of an applied nature, e.g., controlling the population of dust particles in a plasma to prevent contamination of material surfaces.

Furthermore, the experimental techniques proposed in this experiment will develop a novel approach for diagnosing particulate matter in plasmas. Additionally, the infrastructure support provided by this proposed project will ensure the success of the Plasma Sciences Laboratory at Fisk University. Thus, the research component of this CAREER project will be critical to the PI's success as a researcher.

The educational component of this CAREER project will also greatly benefit the career goals of the PI by facilitating providing a forum through which students can be made aware of the importance of the plasma sciences and providing an opportunity to expose and attract talented students to careers in physics. The educational component of this proposal will take advantage of the strong traditions of education and research in physics at Fisk University to expand the existing outreach activities to the high school level. Successful implementation of the educational component will not only forge long-term contacts between local high schools and the Physics Department, but also enhance the role of the university in the community.

The educational and research components are combined in the proposed summer research program for high school students and teachers. In the summer program, the relationships between academic physics, as taught in the classroom, and applied physics, as used in a laboratory environment, are explored. Specifically, concepts in plasma physics, electricity, magnetism, vacuum technologies, and optics are used as the framework to conduct both the research activities and the educational outreach activities. This summer research activity is the cornerstone that supports this project. Thus, awarding of this CAREER proposal ensures the professional success of the PI in his academic career.

6. Personnel

The Principal Investigator (PI) of this project is Dr. Edward Thomas, Jr., a recent recipient of the doctorate in Physics (Auburn University, 1996). He has been Assistant Professor of Physics at Fisk University since August, 1996. Prof. Thomas taught the non-calculus based physics sequence (PHYS 121/122) in the 1996-1997 academic year and will teach the calculus-based physics sequence (PHYS 131/132) in the upcoming academic year. Prof. Thomas is also currently serving as the Director of the Sixth Annual Physics Summer Undergraduate Research Program at Fisk University. In the past year, the PI has also made numerous recruiting trips for the Physics Department and the University.

Prof. Thomas also has extensive research experience in the areas of experimental and computational plasma physics with eight publications and over a dozen conference presentations. Of particular relevance to this project, the PI has performed experiments with hydrogen, helium and argon plasmas produced by both a Hollow Cathode Discharge (HCD) device and by an ECH microwave source. He is experienced at designing, constructing, and operating various plasma diagnostic tools including: Langmuir probes, emissive probes, Mach probes, **E** x **B** probes (omegatrons), ion and electron guns, and gridded-energy analyzers. Dr. Thomas' expertise also includes the design and performance of experiments aimed at characterization, control, and *in-situ* diagnosis of plasma parameters. The PI also has extensive computational experience in modeling vacuum magnetic fields (for stellarator devices), single particle trajectories in toroidal devices, and Monte Carlo simulations of particle emission from ion and electron guns.

Most recently, Dr. Thomas, with start-up funds provided through the Physics Department at Fisk University, has developed an operational plasma source at Fisk. Initial experiments include: characterization of the plasma source, studies of plasma-materials interactions, and preliminary studies of particulate matter in plasmas.

Members of the NASA-Fisk University Center for Photonic Materials and Devices (CPMD) have provided both mentoring and equipment support to the PI of this proposal over the past year and will serve as collaborators on this project. They will provide continued access to diagnostic equipment from the CPMD as well as serving as collaborators in this investigation. Personnel from the CPMD include: Dr. Arnold Burger (Materials Science), Dr. W. Eugene Collins (Surface Science), and Dr. Steve Morgan (Spectroscopy). Additionally, the Auburn Fusion Laboratory, in the Physics Department of Auburn University, will provide the PI with on-line access to its SUN workstations and plasma transport software.

7. Expected Outcomes

This CAREER proposal describes an integrated research and educational program to foster the understanding of dusty plasmas. It is expected that a new optical dusty plasma diagnostic techniques will be developed as part of this research. This technique, particle image velocimetry, will provide new insight into the transport properties of particulate matter in plasmas and the thermodynamic properties of plasma crystals.

These studies will be used as a means to impart the relevance of modern physics research and the importance of the plasma state of matter to students and teachers at local high schools. Through the proposed educational program, long-term contacts between the PI and local schools will be established with the possibility of directly attracting students to the physics program at Fisk University.

8. Figures

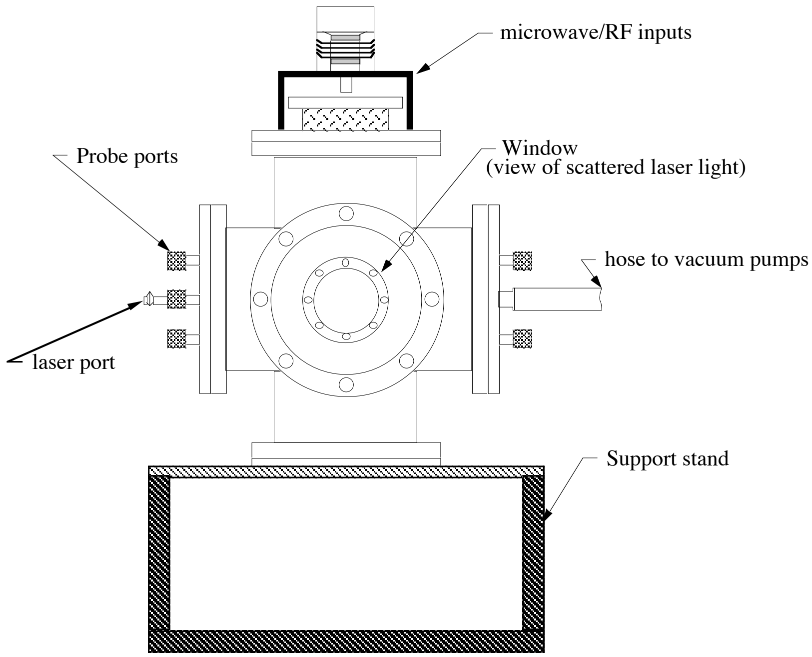

Figure 1: Schematic of the Fisk Plasma Source

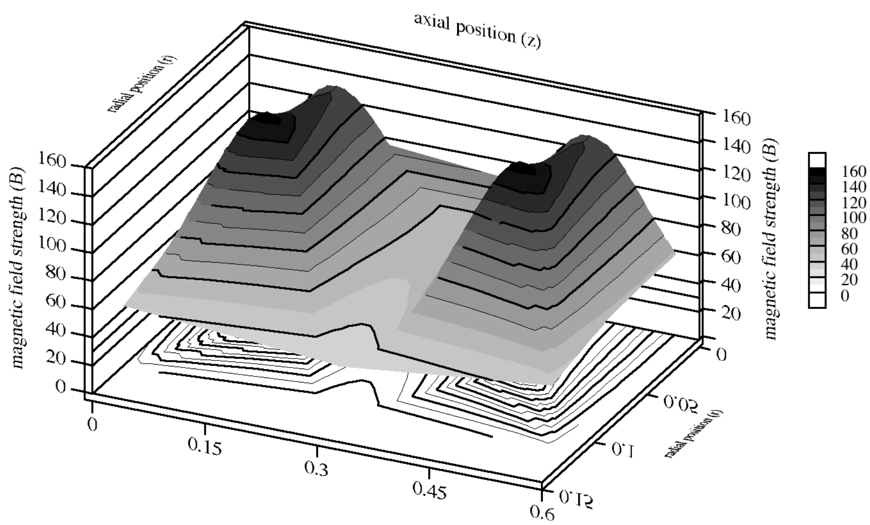

Figure 2: A 3-D contour plot of the magnetic field in the FPS as modeled by the Linear Device Code (LDC). It is shown that the magnetic field in the FPS has a mirror magnetic field configuration with a maximum field strength of ~ 160 Gauss.

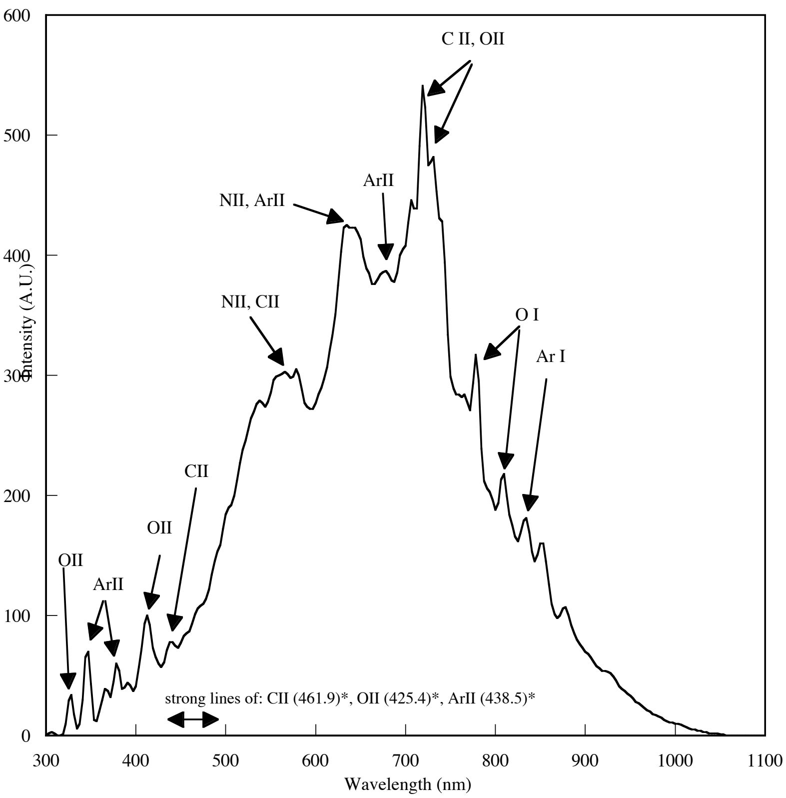

Figure 3: An optical emission spectrum from the plasma created in FPS. It is observed that most of the identifiable emission lines in the visible are from ionized species which is a clear indication of plasma formation.

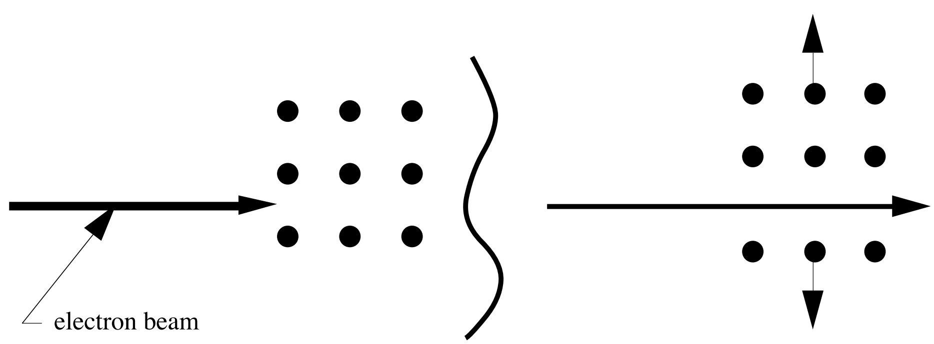

Figure 4: A schematic of the "cleaving" of a plasma crystal by an electron beam. The dots represent individual dust particles in the crystal.