FINAL REPORT

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Project Title: Physics of Magnetized Dusty Plasmas

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Accomplishments

- This grant was funded as part of a collaborative proposal submitted by Auburn University (PI- Ed Thomas), The University of Iowa (PI – R. Merlino), and the University of California at San Diego (PI- M. Rosenberg). The goal of the project is to investigate dusty plasmas in which the electrons, ions, and dust particles are magnetized, i.e., one in which the magnetic force plays a significant role in the dynamics of all three species. The Magnetized Dusty Plasma Experiment (MDPX) was commissioned in May of 2014 and experiments began shortly thereafter. The central scientific equipment of the device is a 4 T superconducting magnet.
- During this grant period the PI of the Iowa grant travelled to Auburn, AL four times, three in which he participated in experiments and one to attend the Workshop on the Physics of Dusty Plasmas. The specific experiments that the IA PI participated in was an investigation of the effect of the magnetic field on the excitation and propagation of dust acoustic waves. During the third week of January 2015, approximately 1 TB of video data was obtained on the dust acoustic waves in experiments performed by the IA PI and AU PI. Along with our theoretical collaborator, M. Rosenberg, analysis of this data is being conducted. Further data will be obtained during the IA PI's visit to Auburn in August of 2015.
- In addition to the dust acoustic wave project, the UI PI participated in the initial experiments conducted by the Auburn and UCSD personnel. The initial investigations have already revealed a new result in dusty plasma physics, an imposed ordered grid structure in the dust suspension. This new result was reported in a Letter to Physics of Plasmas in March 2015 and was also presented in a talk by the AU PI at the Dusty Plasma Workshop.
- The IA PI also participated in experiments investigating the effects of the g x B force on dust particles. The MDPX device is capable of operating with the magnetic field direction either parallel or perpendicular to the acceleration due to gravity, g. In this experiment, g and B were arranged at 90 degrees, and single dust particles were allowed to fall into this configuration. The negatively charged particles were observed to drift in the proper direction. By measuring the deflection of the particles, it was possible to estimate the dust charge. This was the first time that the charge on a dust particle in a high magnetic field was measured. It was found that the dust charge was significantly below the value expected in a non-magnetized dusty plasma. A manuscript on this work is in preparation for submission to Physics of Plasmas.
- Work is also being conducted at the University of Iowa in support of the MDPX. The UI PI has a 0.5 T Q machine available in which investigations of magnetized plasmas (electrons and ions but not dust) can be performed. This device is being used to study the collection of current by a planar probe that can be oriented at an arbitrary angle to the magnetic field. The goal is to study the effect of the magnetic field on current collection. This work is directly relevant to the issue of the charging of dust particles in a magnetized plasma, as well as any application of Langmuir probes in magnetized

plasmas, including probes used in the edge regions of fusion plasmas. The experimental work at the University of Iowa is being conducted with undergraduate physics majors.

Products

- Publications
    - Preliminary characteristics of magnetic field and plasma performance in the Magnetized Dusty Plasma Experiment, E. Thomas, Jr., A. M. Dubois, B. Lynch, S. Adams, R. Fisher, D. Artis, S. Leblanc, U. Konopka, R. L. Merlino, and M. Rosenberg, Journal of Plasma Physics, Published online 25 June 2014.
    - The Magnetized Dusty Plasma Experiment (MDPX), E. Thomas, Jr., U. Konopka, D. Artis, B. Lynch, S. Leblanc, S. Adams, R. L. Merlino, and M. Rosenberg, Jour. Plasma Physics, vol. 81, (2015), doi:10.1017/S0022377815000148.
    - Observations of imposed ordered structures in a dusty plasma at high magnetic field, E. Thomas Jr., B. Lynch, U. Konopka, R. L. Merlino, and M. Rosenberg, Phys. Plasmas 22, 030701, 2015.
    - Quasi-discreet particle motion in an externally imposed, ordered structure in a dusty plasma at high magnetic field, E. Thomas, Jr., U. Konopka, B. Lynch, S. Adams, S. Leblanc, R. L. Merlino, and M. Rosenberg, Phys. Plasmas 22, 113708 (2015).
    - Methods for the characterization of imposed, ordered structures in MDPX, T. Hall, E. Thomas, Jr., K. Avinash, R. L. Merlino, and M. Rosenberg, Phys. Plasmas 25, 103702 (2018).
    - The magnetized dusty plasma experiment (MDPX), R. Merlino, E. Thomas, Jr., B. Lynch, S. Leblanc, T. Hall, U. Konopka, and M. Rosenberg, AIP Conf. Proc. 1928, 020011 (2018).
    - Observation of the dust grain g x B deflection in the Magnetized Dusty Plasma Experiment (MDPX), B. Lynch, U. Konopka, R. Merlino, M. Rosenberg, and E. Thomas, Jr., in preparation for submission to Phys. Plasmas.

- Conference papers
    - Several contributed papers were presented by the AU, IA, and UCSD groups at the annual meeting of the APS DPP held in November 2014.
    - A talk by the AU PI on the MDPX at the 14^{th} Workshop on Dusty Plasmas, May 2015 in Au, Al.
    - Electron and ion currents to a planar probe oriented at an arbitrary angle to the magnetic field in a cesium Q machine plasma, Michael J. McKinlay, Sean M. Harding and Robert L. Merlino (experiments performed at UI).
    - The magnetized dusty plasma experiment (MDPX), R. Merlino, presented at the 12^{th} International Workshop on Non-neutral Plasmas, 10-13 July 2017, Lawrence University, Appleton WI.

- Technologies of techniques
  The initial experiments on the MDPX revealed a new technique for imposing ordered structures in dusty plasmas. This was accomplished by using as the upper electrode of the

RF plasma source, a conducting mesh. By a mechanism that is not yet fully understood, the structure of the mesh was imprinted exactly on the dust particles. This may have implications for plasma processing technologies which are used in the semiconductor manufacturing industry. Further progress on this problem has been made by devising a specific method for characterizing the imposed order.

Participants and other collaborating organizations

- As mentioned above, the MDPX project is a collaborative effort of Auburn University, the University of Iowa, and UCSD. All three PI's have participated in the project during this grant period.
- Several graduate students from the Auburn University Physics Dept. have worked on the project.
- The work performed at the UI was performed with the assistance of two undergraduate physics majors. One of the UI undergraduates is now a graduate student at Auburn University and is working on MDPX. This is the second UI undergraduate physics student who has gone to AU for graduate work in plasma physics.

Impact

- The MDPX is one of only a couple of such devices presently available worldwide and the only one operating in the US. This device opens up an entirely new regime of research into the physics of dusty plasmas
- The work performed on MDPX has potential impact in space science (planetary rings), astrophysics, and fusion science.
- Work on magnetized dusty plasmas has the potential for providing understanding of the structure and dynamics of a ubiquitous component of the universe.
- One of the technical aspects of this research is the investigation of the physics of RF plasma sources under high magnetic fields.
- None of the UI funds were spent in foreign countries during this grant period.

Change/Problems

- No significant changes in the direction or scope of the funded research have occurred in this grant period.
- The MDPX has been in operation for roughly three years. In terms of the performance of the superconducting magnets, this is considered part of the breaking-in period during which the magnetic field would be gradually increased to higher and higher values. Up to this point, operation has been limited to 3 T. Shortly, a scheduled down-time will occur in which the manufacturer will perform routine maintenance on the magnet cooling systems. This is expected to take roughly one month. During the next year of operation, we expect that the manufacturer will give the go-ahead for full operation at the peak field of 4 T. This will enable us to search for direct evidence of the magnetization of the dust particles.