Applying PIV analysis techniques to complex plasmas: reduced gravity, phase transition, and wave experiments

E. Thomas, Jr.[1] and J. Williams[2]

[1]*Auburn University, Auburn, AL, U.S.A.*

[2]*Wittenberg University, Springfield, OH, U.S.A.*

Abstract:

Particle image velocimetry (PIV) techniques have been applied to studies of complex (dusty) plasmas for over a decade. In earlier investigations, measurements were performed using specialized hardware configured specifically for PIV. However, with the increasing use of higher speed video imaging, i.e., >100 frames per second, it is possible to apply PIV analysis techniques directly to video data. This makes it possible to apply PIV to a far wider range of experimental studies including reduced gravity studies and time-resolved measurements of phase transitions and waves in complex plasmas.

Particle Image Velocimetry (PIV):

Complex (or "dusty") plasmas are four component systems consisting of ions, electrons, neutrals, and charged microparticles (i.e., dust). These microparticles, which are typically a few hundred to a few thousand nanometers in diameter, are fully coupled to and integrated with the surrounding plasma – primarily through the collection of ions and electrons from the plasma. In laboratory plasmas, microparticles can collect hundreds to thousands of elementary charges. However, because the mass of these particles is much larger than the ions ($M \geq 10^{14}\ m_{ion}$), the charge-to-mass ratio of these microparticles can be much lower than that of ions. As a result, the spatial and temporal scales of the dynamics of a complex plasma are shifted into a regime where phenomenological scale lengths are L ~ millimeters and time scales are T ~ seconds.

This shift of scales is of particular value in experiments since it means that with the use of standard video technologies, plasma phenomena can be directly observed. Most importantly, it becomes possible to visualize the collective behavior of plasmas as well as the dynamics of individual particles thereby enabling studies at the kinetic level. This is illustrated in Fig. 1 where a photograph of a fluid-like complex plasma in a dc glow discharge experiment is shown.

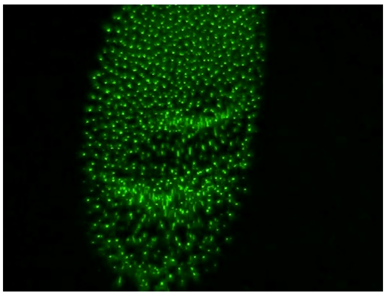

Figure 1: Image of a weakly-coupled complex plasma in the Auburn Dusty Plasma Experiment (DPX). The particle cloud is composed of 3 ± 1 micron diameter silica microparticles. The particle cloud is illuminated using a laser diode at a wavelength of 532 nm. Individual particles and waves are clearly observed in this figure.

Laser light scattering is the most common technique used to diagnose complex plasmas. Here, direct video imaging of the light scattered by the microparticles is captured using a digital video camera. However, a wide variety of other technologies have been adapted to the study of complex plasmas. Advancements in camera technologies, the development of new algorithms to extract detailed position and velocity information from images, and the introduction of fundamentally new techniques such as stereoscopic imaging [1,2] and digital holography [3], have enabled far more detailed information on the transport, spatial structure, and velocity distributions of dusty plasmas to be obtained.

Just over ten years ago, particle image velocimetry (PIV) was introduced to the complex plasma community as another video imaging technology [1,4,5]. PIV is an image analysis technique in which an image is decomposed into a series of interrogration cells. The displacement of particles within a single cell is determined using a cross-correlation between two images that are separated by a time interval, Δt. PIV is considered a "fluid measurement" technique because it does not measure the motion of every particle. Instead, the PIV algorithm computes the average displacement of a small group of particles. The key advantage of PIV is that it is robust, spatially well-resolved, and computationally efficient method of determining the velocities over a large portion of an image. An example of the PIV velocity reconstruction is shown in Fig. 2.

While the majority of the complex plasma studies that have used the PIV technique have made use of specially configured hardware, in principle the PIV algorithm can use any source of images. Thus, with the availability of cameras that can record images at several hundred frames per second (fps), the PIV technique can be applied to a wide variety of experiments.

Recent studies:

Results from two recent investigations in which the PIV technique is used to analyze complex plasmas are described in this paper. The first of these studies involves the melting of a plasma crystal that is described in detail in Ref. [6]. In this experiment, a large plasma crystal consisting of 8.77 ± 0.14 micron diameter melamine-formaldehyde microsphere is formed in the sheath of an argon radio frequency discharge plasma. As the crystal is melted, in this case by decreasing the neutral pressure, there is an increase in the kinetic energy of the particles that leads to an expanding melting region. Figure 3 shows both the image of a rectangular section of the plasma crystal (on the top) and the corresponding velocity (bottom) in a band that is 32 pixels horizontally by 100 pixels vertically. Images are recorded 500 fps. The stable, crystalline region (on the left) is clearly distinguished from the melted region (on the right) with a transitional region in between. Current studies are focused on understanding the propagation of the melting front as a function of time.

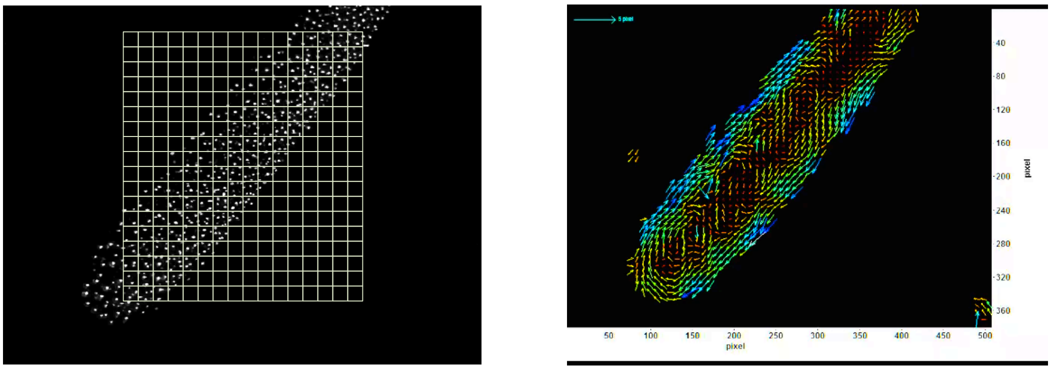

Figure 2: A complex plasma formed in the Auburn Dusty Plasma Experiment (DPX). The particle cloud was illuminated using a continous laser and images were recorded using a Casio Exilim EX-F1 camera operating at 300 frames per second. An example of a typical interrogation grid is shown on the left. The velocity vectors are shown on the right. The reference vector represents a displacement of 5 pixels.

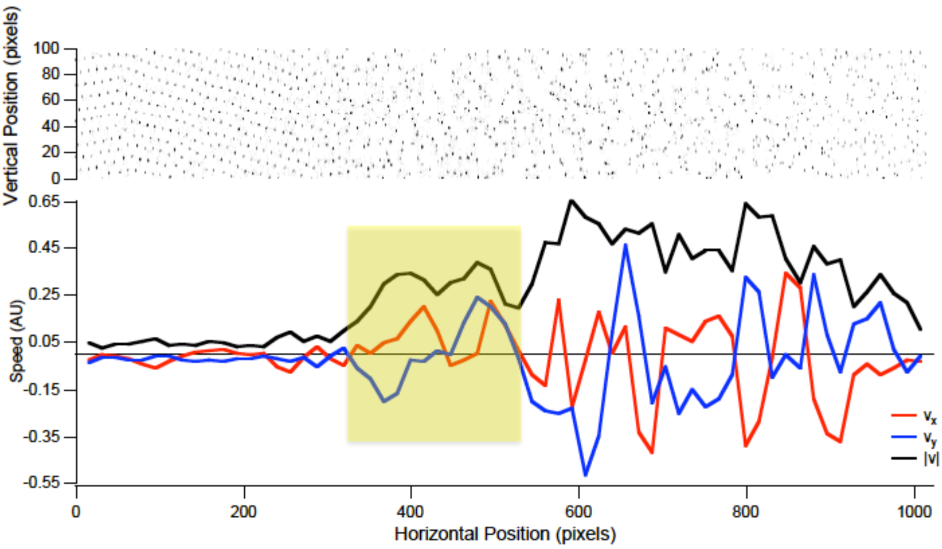

Figure 3: Image (top) and analysis (bottom) of a melting plasma crystal.

A second study uses measurements from reduced gravity experiments with the PK-3 Plus (rf plasma, International Space Station, 50 fps) and PK-4 dc glow discharge experiment (dc plasma, parabolic flight, 500 fps). Here, the PIV technique is used to reveal detailed flow structures in both experiments. In the PK-3 Plus experiment (Fig. 4, left), there are measurements of wave structures at the cloud boundary and a void region is clearly observed. In the PK-4 experiment (Fig. 4, right), there is evidence of strong parallel flow shear in the experiment. Additional analysis of both these reduced gravity experiments is on-going.

The examples shown in Figs. 3 and 4 illustrate the range of possible studies that can be performed using the PIV analysis technique. With continuing improvements in camera technologies and analysis algorithms, it is hoped that PIV will continue to be an important tool for studying the physics of complex plasmas.

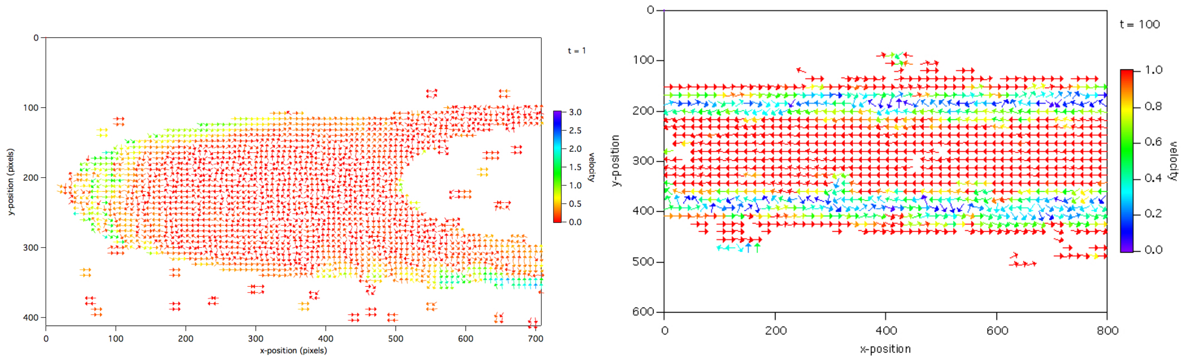

Figure 4: Examples of PIV analysis of complex plasmas under reduced gravity conditions. (Left) Measurement from PK-3 Plus showing evidence of density waves at the left side and the bottom of a cloud in an rf glow plasma. (Right) Measurement from PK-4 showing sheared flows in a dc glow plasma.

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References

[1] E. Thomas, Jr., J. Williams, and J. Silver, Phys. Plasmas, 157 (2004).

[2] S. Käding, A. Melzer, Phys. Plasmas, 13, 090701 (2006).

[3] M. Kroll, S. Harms, D. Block, and A. Piel, Phys. Plasmas, 15, 063703 (2008).

[4] E. Thomas, Jr., Phys. Plasmas, 6, 2672 (1999).

[5] E. Thomas, Jr. and J. Williams, Phys. Plasmas, 13, 055702 (2006).

[6] L. Couëdel, V. Nosenko, A. V. Ivlev, S. K. Zhdanov, H. M. Thomas, and G. E. Morfill, Phys. Rev. Lett., 104, 195001 (2010).