# Laser Heating of 2-D Dusty Plasmas Using a Random Arc Pattern

Zach Haralson and John Goree, *Member, IEEE*

***Abstract*— A laser heating method for 2-D dusty plasmas is improved so that particle motion better resembles thermal motion in a liquid. Laser beams are rastered in a pattern of arcs with three randomly varying parameters: curvature, initial angle, and the speed of the laser footprint as it follows an arc. An experimental test is performed using particle tracking to generate power spectra of velocities. Peaks in these spectra indicate coherence in the particle motion, which is a discrepancy when compared with the stochastic nature of molecular motion in a liquid. We find that spectral peaks are diminished tenfold by rastering with random arcs as compared with a previously used pattern in which beams moved in straight lines at constant speeds.**

***Index Terms*— Complex plasma, dusty plasma, laser heating, liquids, melting, nonequilibrium systems, particle tracking, servomotors, video microscopy.**

## I. Introduction

A 2-D dusty plasma is a partially ionized gas that contains a single layer of small particles of solid matter. These so-called dust particles attain a large negative charge $Q$ by collecting more electrons than ions [1], [2] so that they experience electric forces that can be as strong as gravity. Additional forces acting on the dust particles include a radiation pressure force when they are struck by a laser beam and gas friction when they move through a rarefied neutral gas background [3]. In an experiment, particles are usually electrically levitated and confined by a vertical electric field. The confinement can be shaped so that the dust cloud forms into a single horizontal layer with thousands of particles [4]. The kinetic temperature of the particles can be increased by any fluctuating forces and reduced by gas friction.

At a sufficiently low kinetic temperature, the 2-D dust cloud attains its ground state, which is a triangular crystal with hexagonal symmetry [5]–[7]. Due to a strong mutual repulsion between particles [8], potential energies greatly exceed random kinetic energies, and the interparticle distance is much larger than the diameter of individual dust particles. Such a crystal is soft [9], so it will generally have defects that divide crystalline domains [10]–[12]. These defects multiply if the random kinetic energy is increased, so that the crystal melts [13], [14] and behaves like a 2-D liquid [15].

One way to melt the crystal is laser heating, the application of radiation pressure forces from moving laser beams to enhance the fluctuating kinetic energy of the dust particles [16]. When a laser beam briefly strikes a dust particle, it gives the particle a kick, and thereafter the particle undergoes Coulomb collisions with neighbors, causing motion to randomize.

A laser heating method with beams rastered in a pattern of straight lines, which we will call the triangular Lissajous method, was used by Nosenko *et al.* [17]. They used two beams, directed in the $\pm x$ directions [Fig. 1(a)]. Each beam was pointed at the dust cloud with a two-axis scanning mirror. Mirrors were mounted on servos to deflect the beam by an angle proportional to a voltage from a function generator. Using triangular voltage waveforms, repeating at frequencies $f_x \neq f_y$, a laser beam moved in straight lines to draw a triangular Lissajous pattern that covered a rectangular heating region, as we sketch in Fig. 1(b). The frequencies were chosen to be higher than the frequencies of phonons that compose thermal motion, to reduce unwanted coherent motion. In a dusty plasma crystal, these phonons typically have a maximum frequency of about $0.75\omega_{\mathrm{pd}}$ [18], where $\omega_{\mathrm{pd}} = (Q^2/2\pi\varepsilon_0 m a^3)^{1/2}$ is the 2-D dust plasma frequency, $m$ is the dust particle mass, and $a = (n\pi)^{-1/2}$ is the 2-D Wigner–Seitz radius for an areal density $n$.

Heating with rastered laser beams gives the dust cloud a driven–dissipative character [15]. The driving mechanism is the energy input from the laser beams, while the dissipative mechanism is the frictional damping by the ambient neutral gas. The energy balance of these two mechanisms thus determines the kinetic temperature of the dust cloud.

As a driven–dissipative system, a laser-heated dust cloud is not in thermal equilibrium; nevertheless, the particle motion exhibits some of the signatures of true thermal motion [17]. These signatures include a nearly Maxwellian velocity distribution as well as a temporal fluctuation of the temperature resembling that of a canonical ensemble.

However, laser heating can lead to at least one discrepancy compared with true thermal motion: coherent motion as indicated by peaks in the power spectra for particle velocities [17], [19]. This coherent motion at a particular frequency is caused by the constant-frequency laser rastering, and this effect can be reduced by randomizing the rastering frequency. Another contributing factor, for the coherent motion, is the elongated shape of the laser footprint on the dust cloud; this effect can be diminished by using a larger angle of incidence for the laser beam, with the tradeoff that the heating will be less efficient.

To reduce these spectral peaks, Schablinski *et al.* [19] used frequencies $f_x$ and $f_y$ that the experimenters varied randomly each time a beam was rastered across the heating region. They

Manuscript received July 30, 2015; revised October 2, 2015; accepted October 28, 2015. Date of publication December 1, 2015; date of current version April 8, 2016. This work was supported in part by the Division of Physics, in part by the U.S. Department of Energy, in part by the National Aeronautics and Space Administration, and in part by the National Science Foundation.

The authors are with The University of Iowa, Iowa City, IA 52242 USA (e-mail: zachary-haralson@uiowa.edu; john-goree@uiowa.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2015.2498526

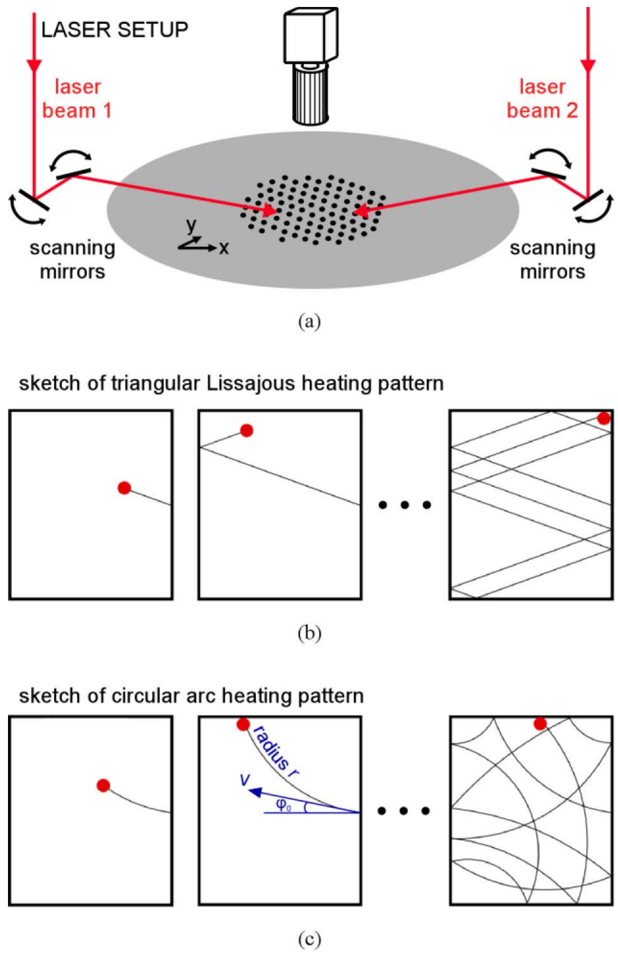



Fig. 1. (a) Sketch of laser heating setup. Dust particles levitated above a horizontal lower electrode are struck by laser beams rastered by mirrors. The chamber is not shown. Sketches of (b) triangular Lissajous pattern and (c) arc pattern.

did not discuss the effect of their frequency randomization on the tendency of Lissajous patterns to retrace themselves, especially when the frequency ratio is near a rational number.

## II. Method

We present another variation on the heating by rastered lasers, which we refer to as the tri-random arc method. The laser beams are rastered in circular arcs instead of straight lines in order to improve the spectral content and uniform randomness of the particle motion and to avoid having the beam retrace similar paths. Moreover, we vary three parameters randomly from one arc to the next: radius of curvature $r$, initial angle $\varphi_0$, and the speed $v$ at which the beam footprint moves, as sketched in Fig. 1(c). We examined arc paths for many candidate sequences of these randomized parameters, and we chose a sequence with 868 arcs that empirically had the best spatial uniformity.

In the experiment, we load this sequence of 868 arcs onto two function generators, which drive the servos for the $x$- and $y$-axis scanning mirrors. We set the timing of the function generators so that the sequence has a duration of 4 s. We repeat this 4-s sequence four times, each time flipping it vertically or horizontally, to comprise a 16-s pattern before the beam retraces itself. A list of the 16 000 data points for the entire pattern is archived for reader use in [20]. The 16-s period is practically infinite relative to the physical time scales: the gas damping time $\nu_{\text{gas}}^{-1}$ and the inverse plasma

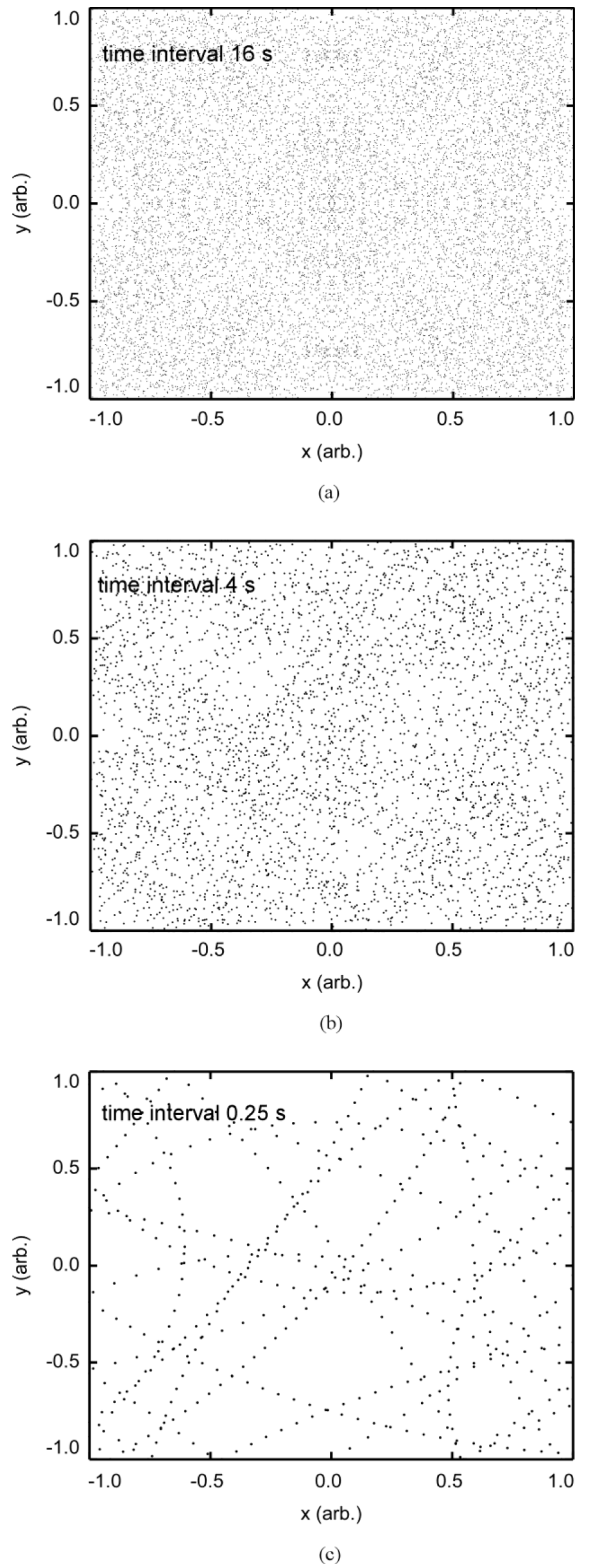
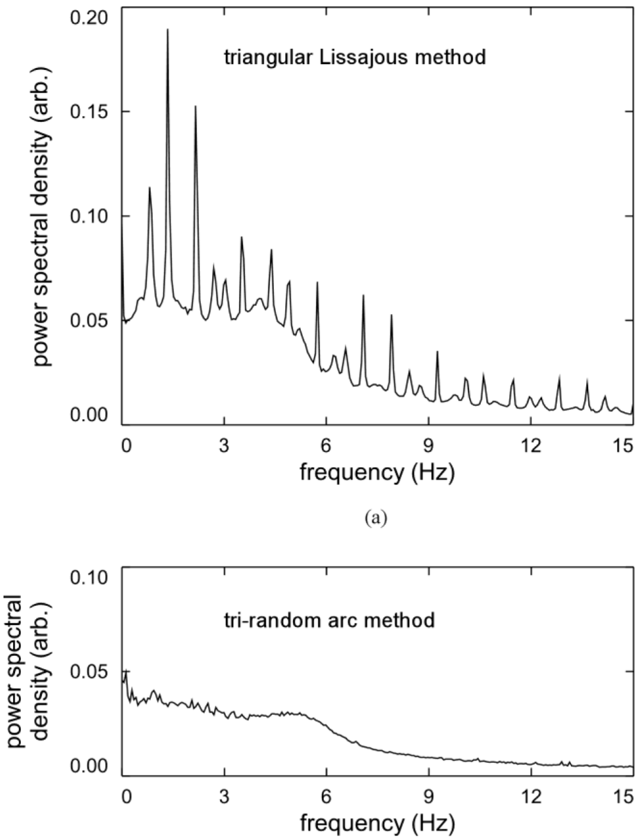


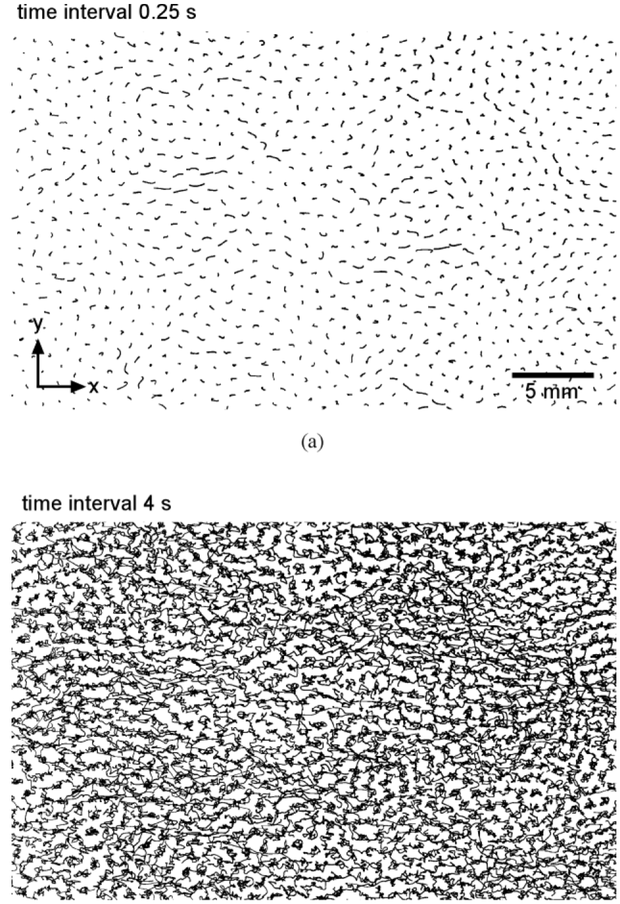

Fig. 2. Programmed positions of a laser beam footprint for the tri-random arc method. The pattern's (a) entire 16-s duration, (b) its first 4 s, and (c) its first 0.25 s. Gaps between data points represent 1-ms intervals.




(a)

(b)

Fig. 3. Power spectra of particle velocities from experimental tests of heating with the (a) triangular Lissajous and (b) tri-random arc methods. Peaks in the power spectrum, which reveal unwanted coherent particle motion, are reduced by a factor of ten when rastering with the arcs.




(a)

(b)

Fig. 4. Particle trajectories, shown as a superposition of video frames in black and white, for heating with the tri-random arc method. Data are from the same video, shown for (a) a time interval comparable to the gas damping time and (b) a longer interval over which our sequence of 868 arcs is traced out once . Motion is generally uniform, becoming more so with a longer observation period, as expected.

frequency $\omega_{\mathrm{pd}}^{-1}$. Here, $\nu_{\mathrm{gas}}^{-1} = m v_d / F_{\mathrm{gas}}$ and $F_{\mathrm{gas}}$ is the drag force acting on a microsphere, as it moves with velocity $v_d$ through the rarefied gas [3]. These time scales were $\nu_{\mathrm{gas}}^{-1} = 0.4$ s and $\omega_{\mathrm{pd}}^{-1} = 0.02$ s for the experiment we describe below.

The three randomly varying parameters in the sequence of arcs were chosen within the following empirically determined ranges. The radius of curvature varied from 0.8 to 8, normalized by the half-width of the heating region. Radii smaller than 0.8 would have the unwanted effect of concentrating the laser beam motion on the perimeter of the heating region, while radii larger than 8 would result in the beam nearly retracing itself. The initial angle of the arcs was varied from 30° to 60°. Angles smaller or larger than this range are undesirable because they cause the beam to spend too much time in the center or perimeter of the heating region, respectively. Finally, the speed of the beam was randomly varied in the range $80 \pm 15$ s$^{-1}$, where distance is normalized by the half-width of the heating region. The frequency content for a back-and-forth beam motion at this speed is higher than 16 Hz, which is above the frequency of natural phonons.

The pattern of arcs is shown in Fig. 2, sampled at 1-ms intervals. Over the entire 16-s time interval, the arcs cover the heating region uniformly [Fig. 2(a)]. The underlying 4-s pattern is shown in Fig. 2(b). The varying radii and angles of the arcs can be seen in Fig. 2(c), which is a portion of the arc pattern on a short time scale comparable to $\nu_{\mathrm{gas}}^{-1}$ and $\omega_{\mathrm{pd}}^{-1}$.

We performed an experimental test of our tri-random arc method using the same plasma chamber configuration as in [21]. Our capacitively coupled RF discharge plasma was made by partially ionizing argon at 20 mtorr. The 13.56-MHz RF had a peak-to-peak voltage of 66 V and a dc bias of −30 V. We introduced our dust particles by shaking them from a dispenser above the plasma. They were 8.69-$\mu$m-diameter melamine-formaldehyde microspheres.

In the experiment, we recorded video data and analyzed the videos to track the motion of the dust particles. We imaged the particles with a 12-bit camera with a 1920 × 1200 pixel resolution (Phantom Miro M120) operated at a frame rate of 60 frames/s. The single-layer dust cloud was illuminated by a horizontal sheet of 577-nm laser light, and a bandpass filter on the camera blocked light at other wavelengths. We measured the particles' coordinates using the moment method [22], [23] and their velocities using particle tracking velocimetry [24]. Power spectra were calculated from the time series of particle velocities [17]. For comparison, we performed this analysis for two ways of heating: 1) our tri-random arc method and

2) the earlier triangular Lissajous method with $f_y = 15.000000$ Hz and $f_x = 24.270510$ Hz.

## III. Results

As our chief result, we find that coherent particle motion is reduced using the tri-random arc method, as demonstrated by the power spectra in Fig. 3. A tenfold reduction of power in spectral peaks is accomplished using the tri-random arc method (Fig. 3).

Spatial uniformity of random particle motion can be qualitatively judged by viewing particle trajectories in Fig. 4. As expected, the uniformity improves for longer time intervals, as seen by comparing trajectories of duration 0.25 s and 4 s. This trend is due to the finite speed of the laser beams as they are rastered across the heating region.[1]

Motion in Fig. 4(b) generally resembles that of molecules in a liquid. Particles are irregularly arranged, and they become displaced by a sizable fraction of the interparticle spacing. There is, however, some anisotropy with displacements in the $\pm x$ directions that are 1.8 times larger than those in the $\pm y$ directions over a time interval of 4.0 s. This anisotropy, which arises from laser beam kicks in these directions, can be reduced using laser beams in more than two directions [19], [25].

## IV. Conclusion

A method of heating a 2-D dusty plasma crystal using rastered laser beams was improved by moving the laser beams in arcs with three randomly varying parameters: 1) radius; 2) initial angle; and 3) speed. This pattern of movement is accomplished by driving scanning mirrors with waveforms that are different from those used in an earlier method with a triangular Lissajous pattern.

We found that this tri-random arc method melts the crystal with reduced coherent motion, compared with the triangular Lissajous method. Coherent motion, as indicated by peaks in the power spectra, is diminished tenfold. The random motion in the 2-D liquid that results from melting the crystal is generally uniform and steady.

## References


[1] P. M. Bellan, "Dusty plasmas," in *Fundamentals of Plasma Physics*. New York, NY, USA: Cambridge Univ. Press, 2006, ch. 17, sec. 3, pp. 559–562.

[2] A. Piel, "Dusty plasmas," in *Plasma Physics: An Introduction to Laboratory, Space, and Fusion Plasmas*. Heidelberg, Germany: Springer-Verlag, 2010, ch. 10, sec. 1, pp. 260–276.

[3] B. Liu, J. Goree, V. Nosenko, and L. Boufendi, "Radiation pressure and gas drag forces on a melamine-formaldehyde microsphere in a dusty plasma," *Phys. Plasmas*, vol. 10, no. 1, pp. 9–20, Jan. 2003.

[4] T. E. Sheridan, "Theory for the breathing mode of a complex plasma disk," *Phys. Plasmas*, vol. 11, no. 12, pp. 5520–5524, Nov. 2004.

[5] J. H. Chu and I. Lin, "Direct observation of Coulomb crystals and liquids in strongly coupled rf dusty plasmas," *Phys. Rev. Lett.*, vol. 72, no. 25, pp. 4009–4012, Jun. 1994.

[6] Y. Hayashi and K. Tachibana, "Observation of Coulomb-crystal formation from carbon particles grown in a methane plasma," *Jpn. J. Appl. Phys.*, vol. 33, no. 6A, pp. L804–L806, Jun. 1994.

[7] H. Thomas, G. E. Morfill, V. Demmel, J. Goree, B. Feuerbacher, and D. Möhlmann, "Plasma crystal: Coulomb crystallization in a dusty plasma," *Phys. Rev. Lett.*, vol. 73, no. 5, pp. 652–655, Aug. 1994.

[8] U. Konopka, L. Ratke, and H. M. Thomas, "Central collisions of charged dust particles in a plasma," *Phys. Rev. Lett.*, vol. 79, no. 7, pp. 1269–1272, Aug. 1997.

[9] Y. Feng, J. Goree, and B. Liu, "Observation of temperature peaks due to strong viscous heating in a dusty plasma flow," *Phys. Rev. Lett.*, vol. 109, no. 18, Oct. 2012, Art. ID 185002.

[10] R. A. Quinn and J. Goree, "Experimental test of two-dimensional melting through disclination unbinding," *Phys. Rev. E*, vol. 64, no. 5, Oct. 2001, Art. ID 051404.

[11] Y. Feng, J. Goree, and B. Liu, "Solid superheating observed in two-dimensional strongly coupled dusty plasma," *Phys. Rev. Lett.*, vol. 100, no. 20, May 2008, Art. ID 205007.

[12] P. Hartmann, A. Z. Kovács, A. M. Douglass, J. C. Reyes, L. S. Matthews, and T. W. Hyde, "Slow plastic creep of 2D dusty plasma solids," *Phys. Rev. Lett.*, vol. 113, no. 2, Jul. 2014, Art. ID 025002.

[13] A. Melzer, A. Homann, and A. Piel, "Experimental investigation of the melting transition of the plasma crystal," *Phys. Rev. E*, vol. 53, no. 3, pp. 2757–2766, Mar. 1996.

[14] T. E. Sheridan, "Melting transition in a two-dimensional complex plasma heated by driven acoustic instability," *Phys. Plasmas*, vol. 15, no. 10, Oct. 2008, Art. ID 103702.

[15] B. Liu and J. Goree, "Superdiffusion and non-Gaussian statistics in a driven-dissipative 2D dusty plasma," *Phys. Rev. Lett.*, vol. 100, no. 5, Feb. 2008, Art. ID 055003.

[16] M. Wolter and A. Melzer, "Laser heating of particles in dusty plasmas," *Phys. Rev. E*, vol. 71, no. 3, Mar. 2005, Art. ID 036414.

[17] V. Nosenko, J. Goree, and A. Piel, "Laser method of heating monolayer dusty plasmas," *Phys. Plasmas*, vol. 13, no. 3, Mar. 2006, Art. ID 032106.

[18] S. Nunomura, J. Goree, S. Hu, X. Wang, A. Bhattacharjee, and K. Avinash, "Phonon spectrum in a plasma crystal," *Phys. Rev. Lett.*, vol. 89, no. 3, Jun. 2002, Art. ID 035001.

[19] J. Schablinski *et al.*, "Laser heating of finite two-dimensional dust clusters: A. Experiments," *Phys. Plasmas*, vol. 19, no. 1, Jan. 2012, Art. ID 013705.

[20] Z. Haralson and J. Goree. (2015). *Waveforms for Tri-Random Arc Heating of Dusty Plasmas*. [Online]. Available: http://ir.uiowa.edu/physics_pubs/5

[21] Y. Feng, J. Goree, B. Liu, and E. G. D. Cohen, "Green–Kubo relation for viscosity tested using experimental data for a two-dimensional dusty plasma," *Phys. Rev. E*, vol. 84, no. 4, Oct. 2011, Art. ID 046412.

[22] Y. Feng, J. Goree, and B. Liu, "Accurate particle position measurement from images," *Rev. Sci. Instrum.*, vol. 78, no. 5, May 2007, Art. ID 053704.

[23] D. Block and A. Melzer, "Imaging diagnostics in dusty plasmas," in *Introduction to Complex Plasmas*, M. Bonitz, N. Horing, and P. Ludwig, Eds. Heidelberg, Germany: Springer-Verlag, 2010, pp. 135–153.

[24] Y. Feng, J. Goree, and B. Liu, "Errors in particle tracking velocimetry with high-speed cameras," *Rev. Sci. Instrum.*, vol. 82, no. 5, May 2011, Art. ID 053707.

[25] A. Melzer *et al.*, "Phase transitions of finite dust clusters in dusty plasmas," *Contrib. Plasma Phys.*, vol. 52, no. 10, pp. 795–803, Nov. 2012.


Authors' photographs and biographies not available at the time of publication.

[1]In Fig. 4, the particle trajectories shown are for the same time duration as the laser patterns in Fig. 2. However, the starting points are different, so that details in Figs. 2 and 4 are not suitable for direct comparison.