Evolution of a Particulate Cloud in an RF Plasma

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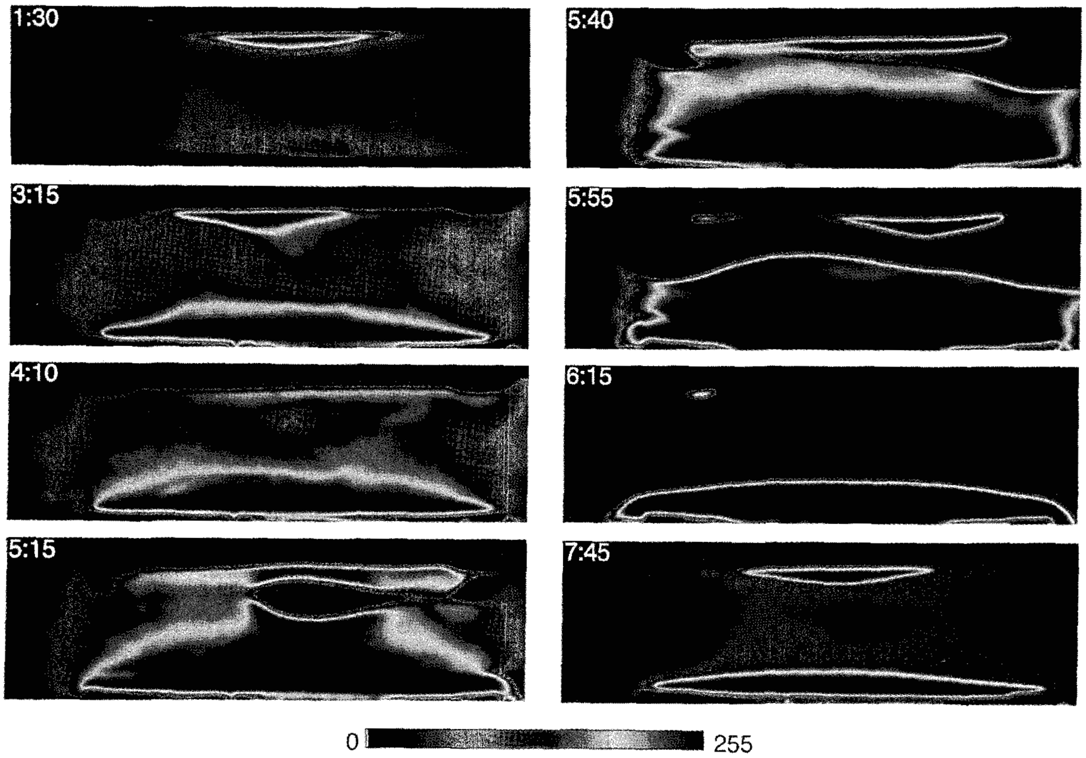

Fig. 1. Images of laser scattering intensity in a carbon dust cloud.

***Abstract*—Video images of a cloud of carbon particulates grown in an RF sputtering plasma show a cyclic process of cloud growth, instability, and collapse.**

PLASMA-generated particulates, ranging in size from a few nanometers to a few millimeters, have been observed in many low-temperature plasmas, including processing plasmas [1], [2] and experimental simulations of dusty plasmas in space [3]. The particulates are negatively charged and can be levitated until the plasma is turned off.

An experiment was performed in a parallel-plate RF reactor with a powered upper electrode [2], [4]. A plasma was generated by 110 W of 13.6-MHz RF power with an argon pressure of 55 Pa. Ions are accelerated by the sheaths to an energy of several hundred eV and they sputter atoms from the graphite target. Particulates can grow from the carbon atom flux by accretion on an existing particle [3], [5]. Particulates are trapped in a cloud in the plasma by a balance between three forces: electric, ion drag, and gravity, which point away from the electrodes, toward the electrodes, and downward, respectively. In the lateral direction, particles are trapped by a gentle electric force directed radially inward [5]. Earlier experiments showed the diameter of our spheroidal particulates grow 15 nm/min during the first 10 min, with a narrow ±6% size dispersion [3]–[5]. This growth rate is consistent with growth by accretion of sputtered neutral carbon atoms [5].

Images show the cloud's temporal evolution (Fig. 1). A vertical sheet of argon–ion laser light (λ = 488 nm) was directed through the discharge region as shown in Fig. 2. The scattered intensity increases rapidly with particle diameter. In this experiment the particulates, too small to be imaged individually, are seen as a cloud. A monochrome NTSC video camera (576 lines resolution) was fitted with a 28-mm Nikon lens and a bandpass interference filter to block the plasma glow. It viewed the scattered light at 45° thus, the dust cloud appears compressed by $1/\sqrt{2}$ in the horizontal direction. The images are digitized by a Scion SG-3 video frame grabber

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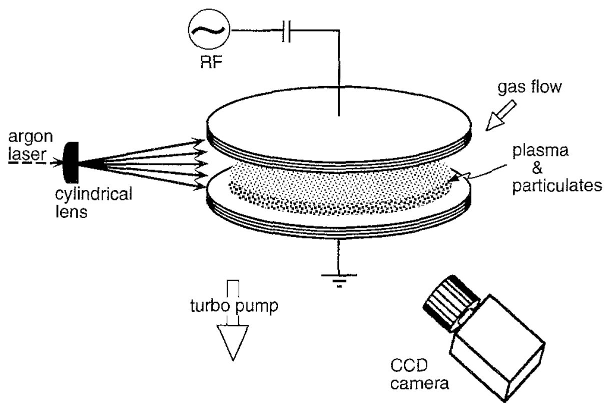

Fig. 2. Sketch of apparatus. The vacuum chamber, which is much larger than the electrodes, is not shown here.

using NIH Image software. Time is denoted here in minutes and seconds (m : ss) from the time discharge was ignited.

Images in Fig. 1 show the full 2-cm high interelectrode spacing. The color bar indicates the video digitizer's 8-bit intensity resolution, red being the brightest. As time passes, a particulate cloud forms near the upper electrode, then goes through a cyclic process of filling the entire glow region, breaking away from the upper electrode due to an instability, and collapsing toward the lower electrode. The instability and collapse are not understood in detail, although they surely involve a change in the equilibrium force balance, which depends on particle size and number density [2].

At $t = 0:00$, the plasma was ignited. A detectable cloud appeared at $t = 0:42$ as a ring (4.5-cm diameter) near the sheath edge at the upper electrode. Beginning with a narrow 1-mm cross-section width, the ring's opening began to close up, and simultaneously, particles flowed downward to the lower electrode. At $t = 1:30$, the cloud filled the entire discharge region, with a greater concentration near the electrodes. Beginning at this time particulates were seen escaping the interelectrode region in the radial direction (the moving video shows this better than the still images).

At $t = 1:51$, an instability started. The cloud throughout the interelectrode region developed an internal filamentary structure (length scale $\approx$3 mm) that vibrated at $\approx$10 Hz. This structure is blue/green near the image center at $t = 3:15$. Voids developed in the cloud at this time, barely recognizable as millimeter-size violet spots at $t = 3:15$ and $4:30$. The instability's frequency diminished to about 1 Hz, and a centimeter-size void opened near the powered electrode (black spot at $t = 5:15$). Further images and discussion of these very low-frequency modes are presented elsewhere [4].

Between $t = 5:40$ and $5:55$, the instability stopped when the cloud divided into a 5-cm diameter ring near the upper electrode and a disk-shaped cloud near the lower electrode. The lower cloud collapsed, as shown at $t = 6:15$. Particulates then apparently ceased to grow in the central plasma region, but were continuously lost radially from the lower cloud, as seen at the radial edges of the lower cloud at $t = 6:15$.

The lower cloud attained its minimum thickness at $t = 7:07$, and thereafter the growth cycle began again. Particles were seen flowing from the lower to the upper cloud, filling the interelectrode region as shown at $t = 7:45$. This cycle repeated until the discharge was shut off.

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