High-Resolution Imaging of a Laser Beam Used to Levitate Opaque Microscopic Particles

Physics 492R Capstone Project Report Submitted to

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Abstract

This report discusses the history of transparent and opaque particle levitation. Various theories explaining opaque particle levitation are explained. An experiment is performed testing the theory that intensity pockets are the main explanation for particle levitation. A 1-micron resolution scan was performed on a Gaussian laser beam that successfully trapped opaque particles. It revealed that there were no intensity pockets of a magnitude that would contribute to the particle levitation. Thus, intensity pockets appear not to be the main explanation for opaque particle levitation since it occurs in a comparatively smooth laser beam.

Chapter I. Introduction

1.1 Overview

Since the early 1960s, lasers have been used extensively in various topics of study. With their use, researchers found that some odd and unexpected things occurred, including propulsion and levitation of dust particles in a laser beam. Rawson and May reported on strangely acting particles caught in a laser beam. It was strange because they consistently moved in one of three directions: "parallel to the laser beam, transverse [perpendicular] to the beam, and at 36° ± 1° to the beam" [1, p.93]. They named the particles that traveled parallel to the beam runners and the ones that traveled perpendicular to the beam bouncers [1]. In 1966 they offered a theory on why it worked which later led to the radiometric levitation theory. Unfortunately, the forces involved were too small to measure at that time and their work was largely forgotten.

Later, Ashkin performed a series of experiments in which he trapped transparent particles in a gas or liquid. First he used a single laser beam to trap the particles and found that the particles were "drawn into the beam axis and accelerated in the direction of the light" [2, p.156]. To create a stable trap for the particles, he used two laser beams directed in opposite directions along the same axis. In future experiments, Ashkin developed a process for trapping transparent particles called optical tweezers. He explained that the trapping works because as the particles move away from the center of the beam, the light passing through the particle is

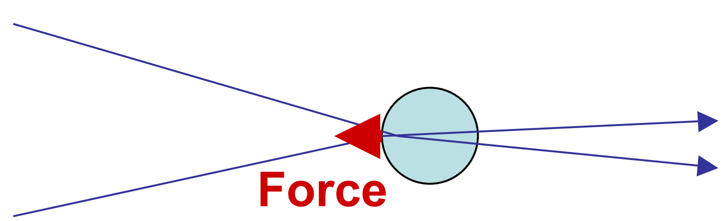

Figure 1.1: Transparent particle being forced back into beam.

deflected, causing a restoring force that pushes the particle back to the center of the laser beam. Figure 1.1 shows an example of how the force acts on a transparent particle to keep it in the beam [2]. This is how most trapping is done today, but it only works on transparent particles.

Years later, Lewittes noticed that opaque particles could become trapped in his laser beam. Not knowing of the work done previously by Rawson and May on moving particles, Lewittes studied the trapping of particles and came to a similar conclusion for the primary mechanism involved. That is, the particles are heated by the laser and the surrounding air molecules impart momentum as they recoil from the heated surfaces. Lewittes proposed that the particles stabilize in the laser beam because of intensity pockets that existed in his beam. He thought that the difference in the intensity created a well in the middle of the beam with higher intensities on either side (see Figure 1.2) [3]. Lewittes thought that gravity must play a part in the trapping and, because of this, always directed the laser beam vertically with the laser pointing upward from below. However, the following year Pluchino [4] did work that cast doubt on many parts of Lewittes' theory. For instance, it was found by Pluchino that the beam could be

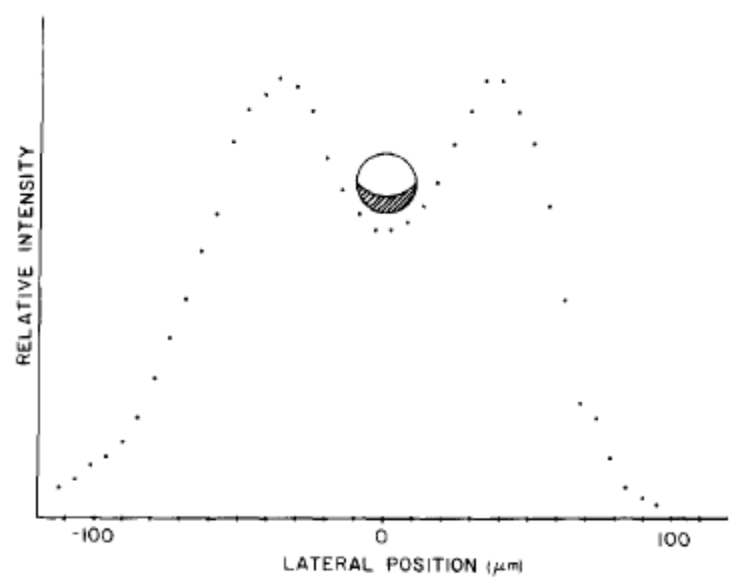

Figure 1.2: Proposed idea of intensity well to trap a particle when laser is directed from below (picture from Lewittes [3]).

oriented in any direction [4], thus downplaying the direction of the laser beam and the role of gravity in particle levitation. Pluchino proposed that the laser beam diffracted around the particle, wrapping around to the back side and actually depositing more light there. He used this theory to explain why particles apparently sought regions of the laser beam with higher intensity where they became trapped.

More recently, Huisken and Stelzer [5] studied the phenomenon and argued again in favor of the heating of the particles and interaction with surrounding air molecules as the primary mechanism. They proposed that the phenomenon is related to thermal creep, which is the primary mechanism for turning the veins in Crookes' radiometer. However, Huisken and Stelzer did not explain why the trapping is stable. Again, they directed their beam upwards to counteract the force of gravity.

The theory that explains why transparent particles can be trapped (i.e., based on momentum imported from the light) predicts that opaque particles should be pushed out of the laser beam, not held within it. The same laser beam rays that would pass through a transparent particle and hold it in place would bounce off of the surface of an opaque particle and the resulting force should push it out of the beam. However, as outlined above, self-selecting opaque particles can become trapped in laser beams, but the mechanism appears to have much to do with heating of the surrounding air molecules rather than the momentum of the light.

Our group at Brigham Young University has tested several aspects as to how this occurs. Past students in our group found that the trapping of opaque particles does not work in vacuum or under water. They found that there must be air (or another gas) present with a pressure between a few torr and several atmospheres. They found that nearly any kind of material can be trapped if the particles are smaller than about 10 microns. They found that the beam can be pointed in any direction and that phenomenon still works when the apparatus is in free fall. Many of these experiments are explained in greater detail in Section 1.3. For my project, I investigated whether the laser beam needs to have structure (i.e., low-intensity pockets) in order to accommodate the trapping phenomenon. I developed a measurement technique with 1-micron spatial resolution to measure the intensity profile of our laser beam. As will be described in Chapter 2, I found that an extremely smooth laser beam can still trap particles.

1.2 Possible Explanations

Many opinions as to why particle levitation actually works have been offered. One theory relies on convection currents, radiometric levitation, and intensity pockets or wells. Through a series of experiments, our group has discredited the last theory, although we do not have a proven replacement theory yet.

Convection currents originate from air that is heated and rises because of the effects of gravity. That is because hot air expands and becomes less dense than cooler air. It then flows upward and allows cool air to flow downward because the hot air is lighter. This could cause the particles to levitate in the laser beam because such convection currents might push up on the particle and support it (see Figure 1.3).

Figure 1.3: Convection currents push up on a particle to support its levitation. [6]

Radiometric levitation derives its name from Crooke's Radiometer because it uses generally the same theory to explain what happens. It depends on a temperature gradient along the surface of the rotating veins. In a process described as "thermal creep," the gas molecules sometimes move from a colder region to a warmer region without thermalizing, owing to a long mean-free path. This creates a pressure difference that allows the vein to rotate. We suspect that something like this is happening also with the radiometrically levitated particles. Normally, this would not be possible in macroscopic air flow. However, as the size of the particle is within the mean-free path of the gas, there is a drop in air viscosity, known as “slip” and this is what potentially allows the thermal creep to happen on the microscopic level. This theory is recommended more than once in various journal articles, but is difficult to prove or disprove experimentally. Additionally, while this seems like an important and likely mechanism, it is not clear how this can account for the trapping of the particles.

As explained earlier, Lewittes was the first to propose the idea of an intensity pocket or intensity well in the laser beam that holds and levitates a particle in a stable spot. Figure 1.2 is reproduced here again for reference (see Figure 1.4). The theory is that there are distortions created in the laser beam that cause intensity pockets or wells to be found within the laser beam. As shown in Figure 1.4, the particle is caught in this well and is stable there because the high intensity of the walls contains it. Originally, many experiments were designed to purposefully create an intensity well. We have discovered experimentally that distortions in the laser beam allow us to trap particles more easily. However, even when an apparently smooth Gaussian laser beam is used, the particles still trap easily.

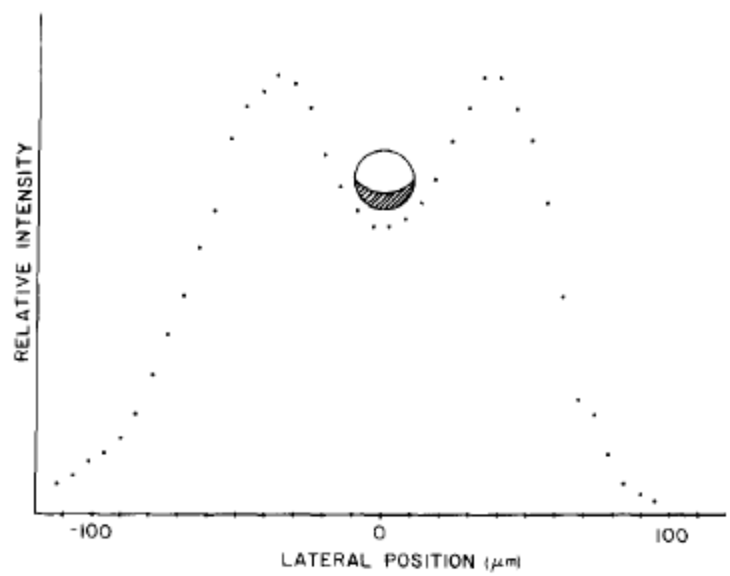

Figure 1.4: Proposed idea of intensity well to trap a particle when laser is directed from below (picture from Lewittes [3]).

1.3 Work at Brigham Young University

It seems that this intriguing problem associated with particle levitation has been stumbled upon accidentally by various research groups. This happened at Brigham Young University (BYU) as well and the first students to study particle levitation were C. Bliss [6] and B. Bellville [7]. C. Bliss trapped a variety of particles of different metals and different sizes to see what worked. The particles ranged in size from 1 μm to 30 μm. They found that particles trap better at a higher pressure (~200 torr) than at a lower pressure (~7 torr) and that an ambient gas is necessary for the laser beam to trap particles. John Painter showed that particles remain trapped in the laser beam during free fall [8]. A. Hendrickson and R. Lindsey studied how trapped particles quiver in the laser beam. Particles execute orbits along the laser axis with excresion distances on the scale of tens or even hundreds of microns. They also observed that particles undergo accelerations as high as 10 g [9, 10].

The levitating particles choose very particular spots in the laser beam. This supports the theory that there are intensity pockets in the laser beam in which the particles levitate. However, J. Painter at Brigham Young University closely examined the laser beam with a CCD camera looking for diffraction pockets or intensity pockets to explain the trapping of the particles. He did not find anything and the laser appeared very smooth [8]. However, a CCD camera has limitations in its ability to look closely because the size of the pixels is 10 microns by 10 microns. Therefore, it was not conclusive, especially since many of the particles were smaller than 10 microns.

An important factor involved with convection currents is gravity. However, an experiment was performed by J. Painter at Brigham Young University in which he was able to perform the trapping of the particles in about 0.5 seconds of free fall. The particles verifiably remained trapped in the laser beam during the entire fall, discounting the effects of gravity. Another group of BYU students had the opportunity to reproduce this experiment in 25 seconds of freefall on NASA's Microgravity Experiment in Texas. They found that the particles remained trapped during each of the freefalls. Their results discount the effects of gravity and, thus, convection currents on opaque particle levitation.

1.4 Searching for Intensity Pockets with 1-Micron Resolution

For my capstone project, I designed an experiment to search for intensity pockets within an apparently smooth Gaussian laser beam in order to determine if they were a major contributor to opaque particle levitation. I received valuable assistance from another undergraduate student, Matthew Turner. We scanned a 1-micron pinhole through the laser beam to create a cross-sectional picture of the beam with 1 micron resolution. As explained earlier, the previous experiments using a CCD camera were inconclusive since they were limited by 10-micron resolution. Since many of the particles that we trap in the laser beam range from 4-13 μm, there could exist intensity pockets helping the particles trap that are not detected with the CCD camera. However, with the smaller resolution, any difference in intensity that affects the particles should be perceptible. Upon close examination of the Gaussian laser beam, we found it was relatively smooth and lacked any intensity pockets that could be the principle reason for the trapping of the opaque particles.

Chapter II. Experimental Setup

2.1 Laser Beam Setup for Levitating Particles

Initially, we had to trap particles in the laser beam so that we could find the areas where a particle was stably trapped. Since these were the areas with the highest likelihood of intensity pockets, we wanted to scan the laser beam at those points. We used a Coherent Verdi laser to trap the particles. It is a 5-watt laser that produces a green laser beam with a wavelength of 532 nm. We set the laser beam at 4 watts for all of the trapping and scanning of the laser beam. The laser was setup and designed to produce a smooth, Gaussian laser beam. This is important because a smooth laser beam should not have any of the intensity wells or pockets that we were hoping to find in our experiment. Although the laser beam may appear to be smooth, we expected at the smaller resolution to find small intensity wells undetectable at a larger resolution.

The laser beam passed through a series of lenses and mirrors before trapping the particles as shown in Figure 2.1. The particles trap easier in the laser beam if the beam enters the second lens with the largest possible diameter. The first lens has a 15 cm focal length and is placed in the beam to broaden the laser beam diameter. Mirrors are used to

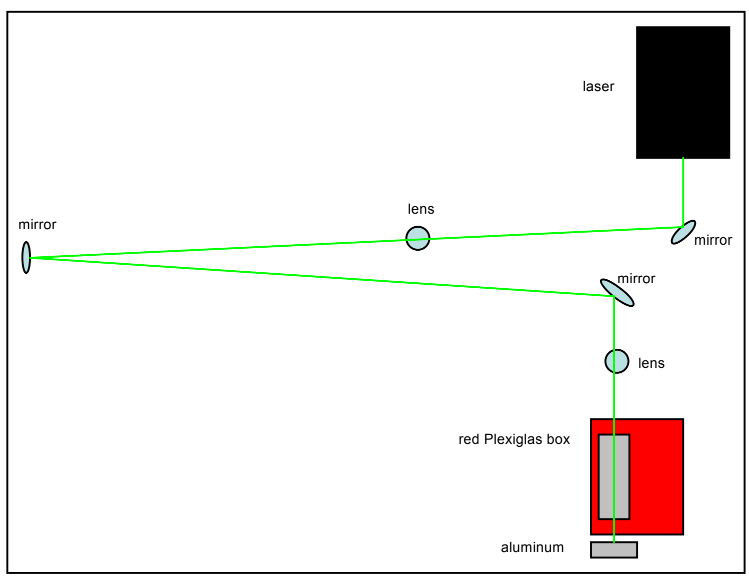

Figure 2.1: Diagram of setup for trapping particles.

give the beam a longer distance between the two lenses so that the beam enters with a large diameter into the second lens which has a 10 cm focal length.

After passing through the second lens the laser beam then entered a red Plexiglas box through a small hole in the side. Figure 2.2 shows a picture of the plastic box used to create an environment for trapping that is free of air currents. There was an opening on top of the box where the particles could be sprinkled in the laser beam and be trapped. We placed aluminum foil under the box to catch all of the particles that did not trap or that fell once we turned the laser beam off. On the opposite end of the box we placed a painted block of aluminum to stop the laser beam from going elsewhere in the lab.

Figure 2.2: Picture of box for trapping particles.

Once everything was in place and the laser beam was properly lined up, we used a cotton tip swab to sprinkle graphite particles into the laser beam near the focus. The self-selecting particles that trapped were visible by the brilliant scattered light that made them appear like little stars. We measured the distance from the lens to where the particle was trapped and marked that as our zero point on the z-axis. The z-axis is parallel to the laser beam propagation and we used this for reference when creating our cross-sectional pictures of the laser intensity profile.

2.2 Setup to Scan Laser Beam with 1 Micron Resolution

Once we determined the location of the trapped particle, we briefly turned off the laser in order to switch out the particle trapping equipment and replace it with the micrometer setup used for scanning the laser beam. The diagram of the micrometer setup is shown in Figure 2.3. In order to create a 1-micron resolution scan of the laser beam, we used a 1 µm pinhole (see Figure 2.4) to scan through the laser beam. We created an aluminum faceplate that the pinhole fit into and attached that to a photomultiplier tube or PMT. The PMT behind the pinhole detected the intensity of the light at each position and fed it into the computer and its program. The computer program recorded several measurements at a single position and then used the average of those measurements to create the final data point used in analysis. To ensure accuracy in the positions of each scan and measurement recording, we attached the pinhole and PMT to a pair of micrometers that were also controlled by the computer program. One of the micrometers moved along the x-axis while the other moved along the y-axis. The program moved the pinhole through the laser beam in a grid-like pattern, scanning down a row and then moving down a row to scan down the next one. The increments between rows and

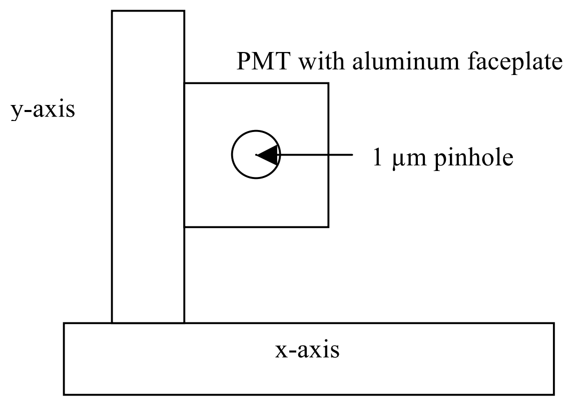

Figure 2.3: Diagram of micrometer setup.

Figure 2.4: Picture of 1 µm pinhole.

positions for taking measurements were small, between 2 and 5.5 µm. Since the particles trapped in this laser beam during this experiment and at other times were generally on the order of 4-13 µm, this step size and resolution were appropriate for discovering any intensity wells that may have contributed to the particle trapping. In order to fully explore the laser beam and its structure, we also had a small micrometer that moved the pinhole parallel to the z-axis and the laser beam (see Figure 2.5). We took complete cross-sectional scans of the laser beam at the point where the particles was trapped as well as at several points both upstream and downstream in the laser beam.

Figure 2.5: Picture of micrometer setup.

We scanned the laser beam in 2 µm intervals up to 10 µm both up and downstream. We labeled these points as z=-4 µm, -2 µm, 0 µm, +2 µm, +4 µm. In this way, we could get a clear picture of the laser beam at the point of interest and surrounding areas. Scanning the laser beam at a resolution of 1 µm and having data for close intervals along the z-axis enabled us to detect the intensity wells in the laser beam, if any.

Chapter III. Results

3.1 Measurements of Intensity of Laser Beam Cross-sections

Figures 3.1-3.5 show cross-sectional pictures we created of the laser beam at z=-4 µm, -2 µm, 0 µm, 2 µm, and 4 µm, respectively. The colors represent the intensity of the laser beam where blue is a low intensity and red is high intensity. Each picture is scaled slightly differently because the laser beam got tighter closer to the focus.

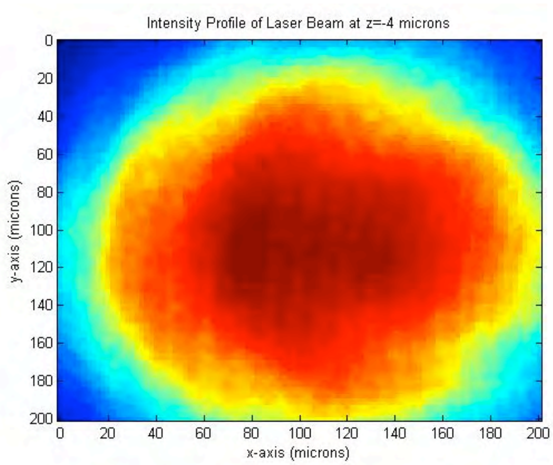

Figure 3.1: Cross-sectional picture of the laser beam's intensity at z=-4 µm (upstream)

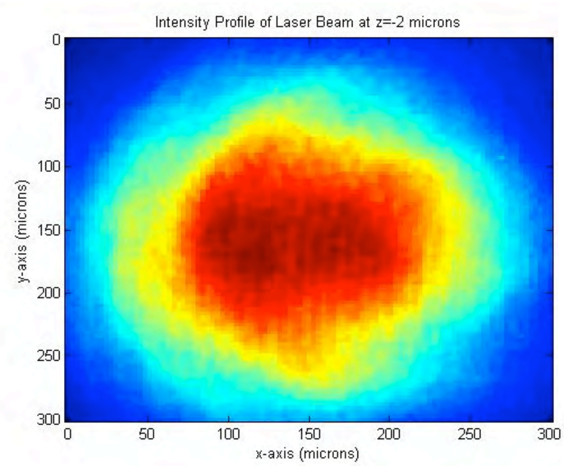

Figure 3.2: Cross-sectional picture of the laser beam's intensity at z=-2 µm (upstream)

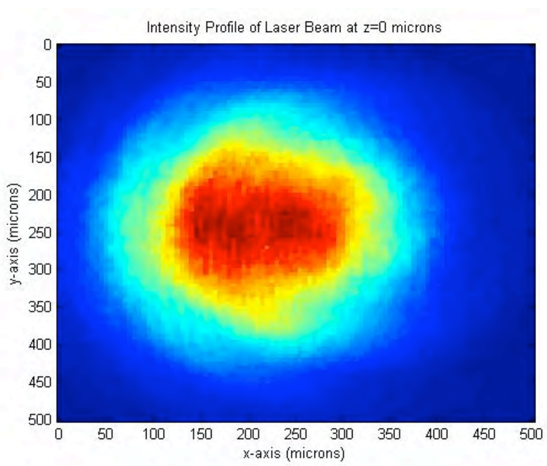

Figure 3.3: Cross-sectional picture of the laser beam's intensity at z=0 µm (trapping spot)

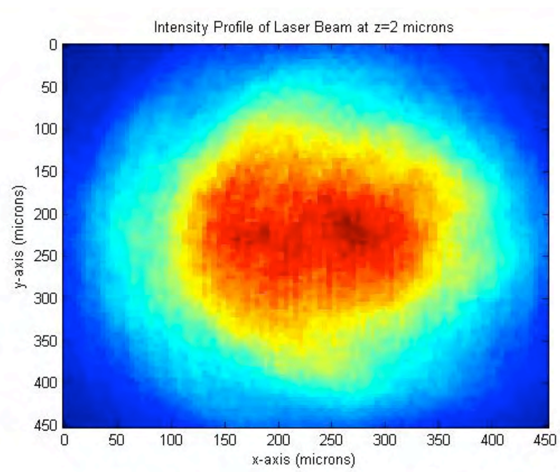

Figure 3.4: Cross-sectional picture of the laser beam's intensity at z=2 µm (downstream)

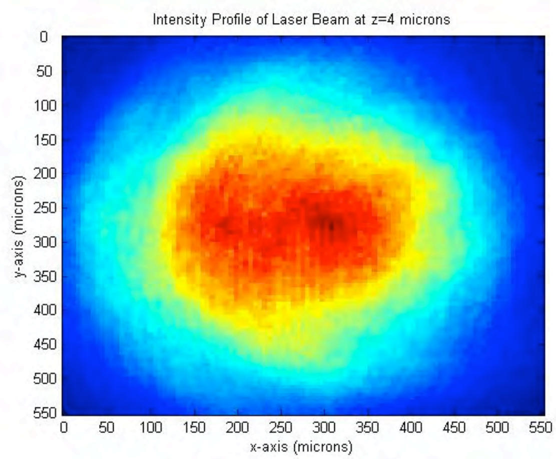

Figure 3.5: Cross-sectional picture of the laser beam's intensity at z=4 µm (downstream)

Clearly, the laser beam is relatively smooth. There do not appear to be any significant intensity pockets that could accommodate the trapping of a particle that flees high intensity. Even though distortions in the beam can help particles trap more easily, there are no intensity pockets in this Gaussian laser beam. It is interesting to note that the particles appear to have trapped downstream from the focus in the laser beam as opposed to upstream.

As shown in the previous pictures, Figures 3.1-3.5, the laser beam effectively traps opaque particles without the presence of any intensity pockets detectable at a 1-micron resolution. Thus, intensity pockets are not the main explanation of opaque particle levitation since it can be accomplished in a comparatively smooth laser beam. Further experiments can be performed to determine an explanation for the levitation of opaque particles.

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