Construction and Implementation of a Novel Dust Dropper for the PPPL DPX

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Abstract

The applications of dusty plasma research are far-reaching, from understanding astrophysical systems to studying plasma-wall interactions in magnetically-confined plasma experiments. Unfortunately, dusty plasma environments can be difficult to control and replicate in laboratory settings. This poster details the construction, vacuum operation, and initial results of a multifaceted dust dropper, which is being implemented in the Princeton Plasma Physics Laboratory Dusty Plasma Experiment (DPX). The cylindrical polyoxymethylene (POM) shaker comprises four pairings of electromagnets and neodymium magnets, with eight stabilizing springs. The amplitude and frequency of a pulsed current determine the dust dispersal rate, while a biased metallic mesh regulates the area of dispersion and size, charge, and velocity of dropped particles. Dispersal rates from 100 to 10,000 particles/s are observed, and reproducibility of dust cloud formation is achieved.

Introduction

Normal plasma = Electrons + Ions + Neutral atoms
Dusty plasma = Normal plasma + Granular particulates (nm-µm)

Dusty plasma research is relevant to many areas of science:

- Astrophysics – Interstellar media [1]
- Technological processing – Computer chips and thin films [1]
- Magnetically-confined plasma experiments – Fusion research [2]

Motivation

Dusty plasma environments are difficult to control and reproduce. Previously, dust was randomly dispersed by arcing between the anode and collector plate (Fig. 1).

The purpose of this project is to construct and implement a dust dropper that can

- Be implemented in many experimental setups
- Regulate the size, charge, and initial velocity of dust particles
- Control the dispersal rate and area of dispersion of a dust sample
- Form reproducible dust clouds without the need of unstabilizing arcing

DPX Setup

The current setup of the DPX is shown in Fig. 1. Dust clouds form in the region between the anode and collector stand. [3]

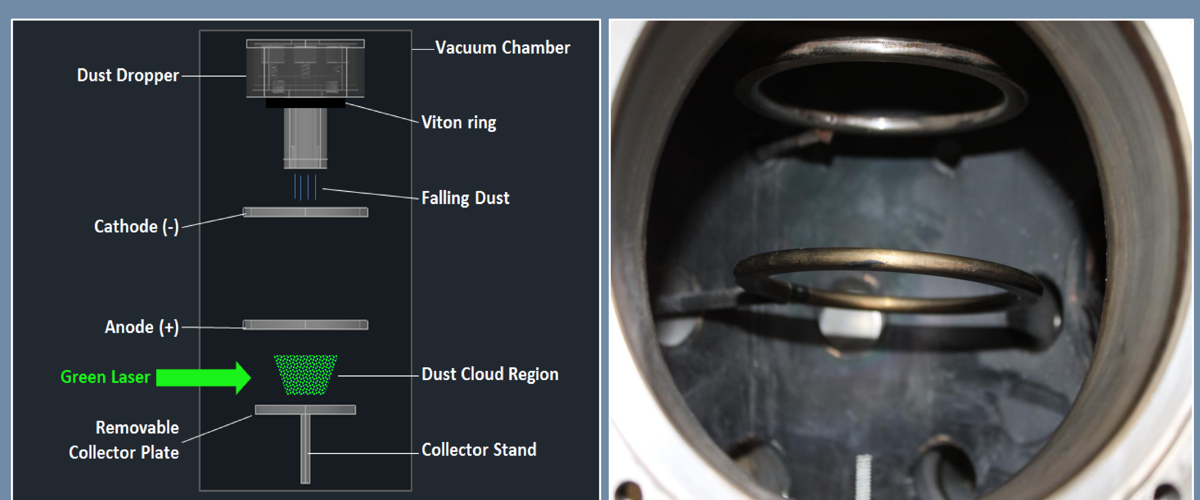

Figure 1. Left: Diagram of the DPX setup. Right: Photo of the cathode (top), anode (middle), and POM support (bottom) in the vacuum chamber.

Design

The presented design (Fig. 2) of the dust dropper includes

- POM outer housing and inner shaker
- 4 electromagnets (211 turns each)
- 4 neodymium permanent magnets ($B_{max} \approx 0.3$ T)
- 4 top springs ($k_{top} \approx 1350$ N/m)
- 4 bottom springs ($k_{bottom} \approx 2400$ N/m)
- Biasable stainless steel mesh (178 micron openings)
- Spherical agitator [4]
- 44 micron silica (SiO_2) dust

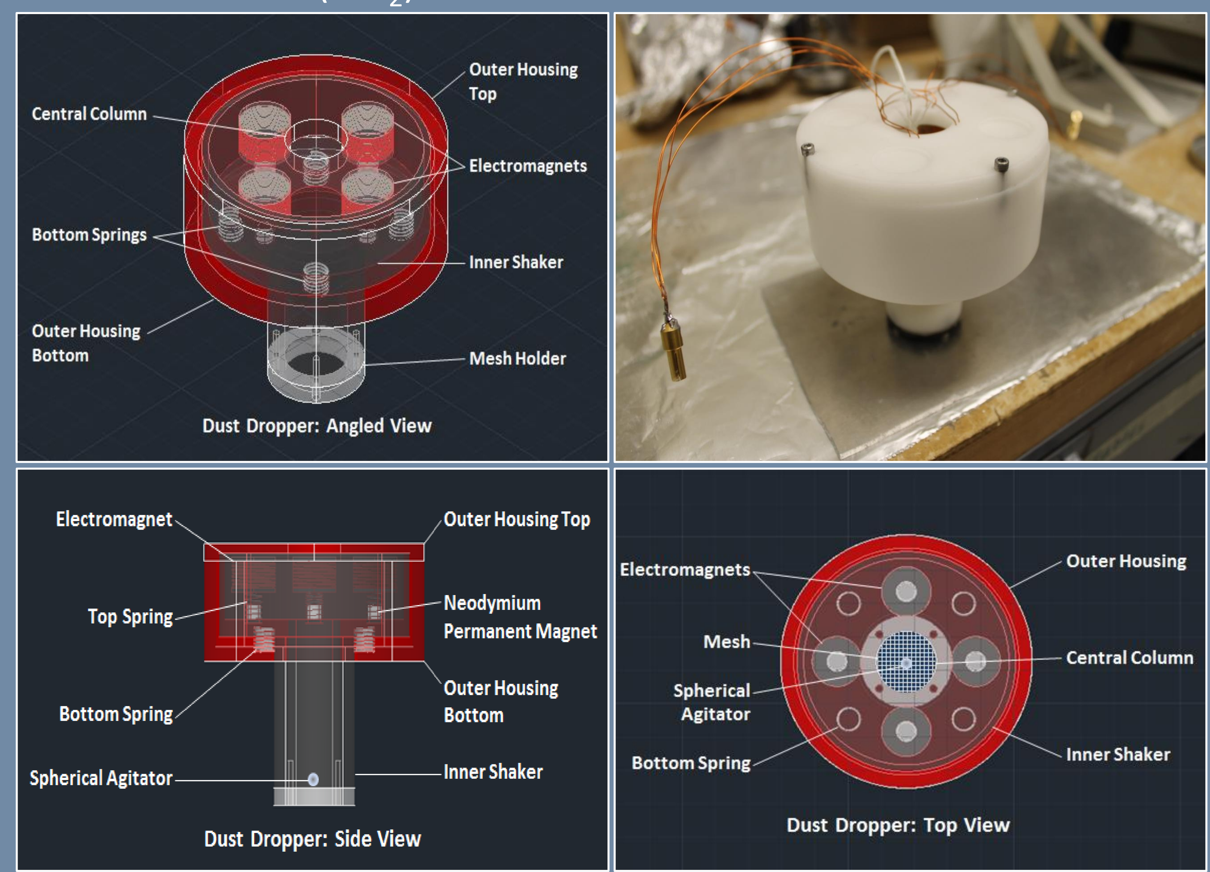

Figure 2. Diagrams of the dust dropper from three views. Upper Right: Photo of the dust dropper.

Motion of the Shaker

A function generator supplies voltage pulses of duty cycle 5% to the dust dropper via an amplifier (Fig. 3).

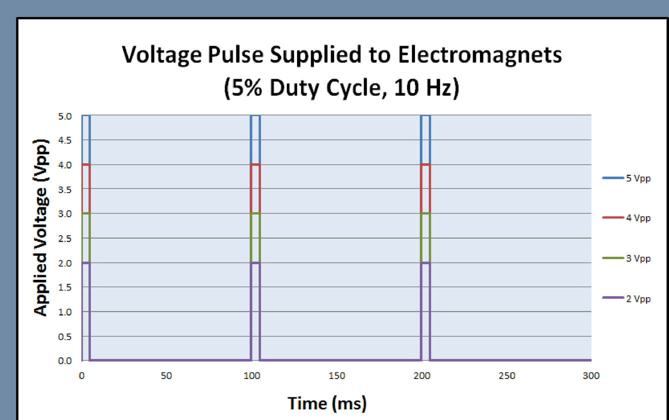

Figure 3. Voltage waveform supplied to the electromagnets. Different voltage amplitudes are used to vary the drop rate.

The driving force, $F(t)$, of the shaker can be written as a Fourier expansion of these periodic pulses of amplitude F_0, duty cycle D, and frequency ω:

$$F(t) = F_0\left(D + \frac{1}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\left(\sin(2\pi nD)\cos(n\omega t) + (1-\cos(2\pi nD))\sin(n\omega t)\right)\right)$$

The shaker behaves as a driven damped oscillator with equation of motion:

$$\ddot{z}(t) - \gamma\dot{z}(t) + \omega_0^2 z(t) = \frac{F(t)}{M}$$

The instantaneous power delivered to the system is the product of the force and velocity (as determined from the solution of the equation of motion). The time-averaged power delivered to the dropper is

$$\langle P(\omega)\rangle = \frac{\gamma}{M}\left(\frac{\omega F_0}{\pi}\right)^2 \sum_{n=1}^{\infty}\frac{1-\cos(2\pi nD)}{(\omega_0^2 - n^2\omega^2)^2 + (\gamma n\omega)^2}$$

Results

Resonant Frequency

The experimental resonant frequency of the dust dropper ranges from 7 to 10 Hz. The motion of the dropper is most consistent with that of a driven underdamped oscillator with damping coefficient of approximately 150 s^{-1} (Fig. 4).

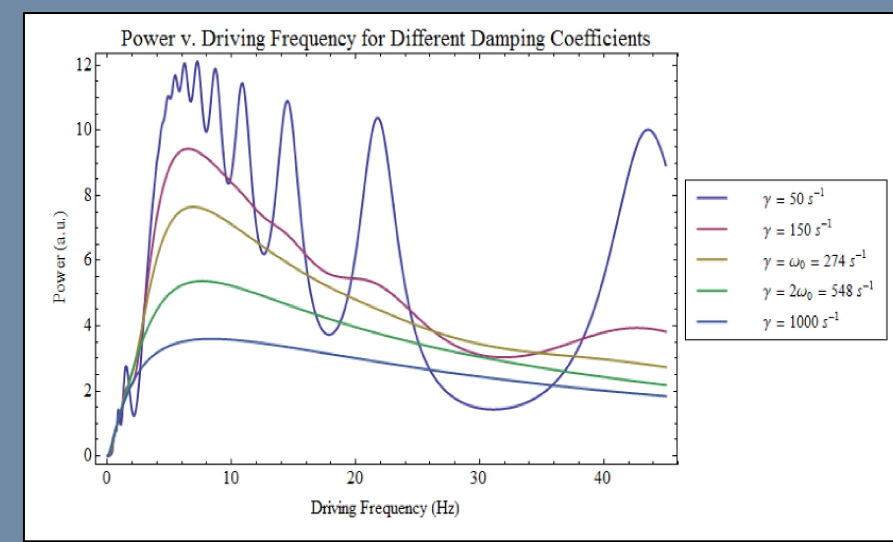

Figure 4. Power absorbed by the shaker for several damping coefficients.

Dust Dispersal Rate

At resonance, dust dispersal rates tend to:

- Increase as the applied voltage increases (Fig. 5).

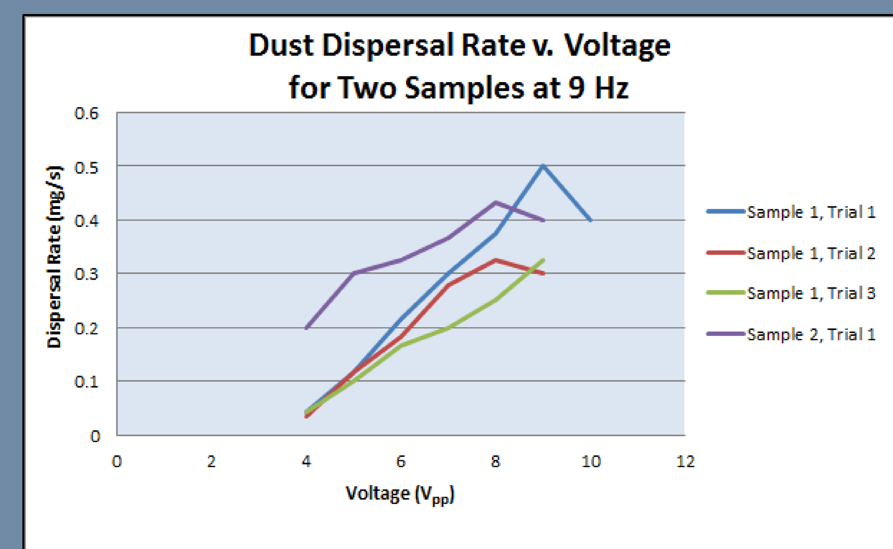

Figure 5. Dust dispersal rates for two dust samples.

- Exhibit strong sensitivity to the conditions of a dust sample (Fig. 6).

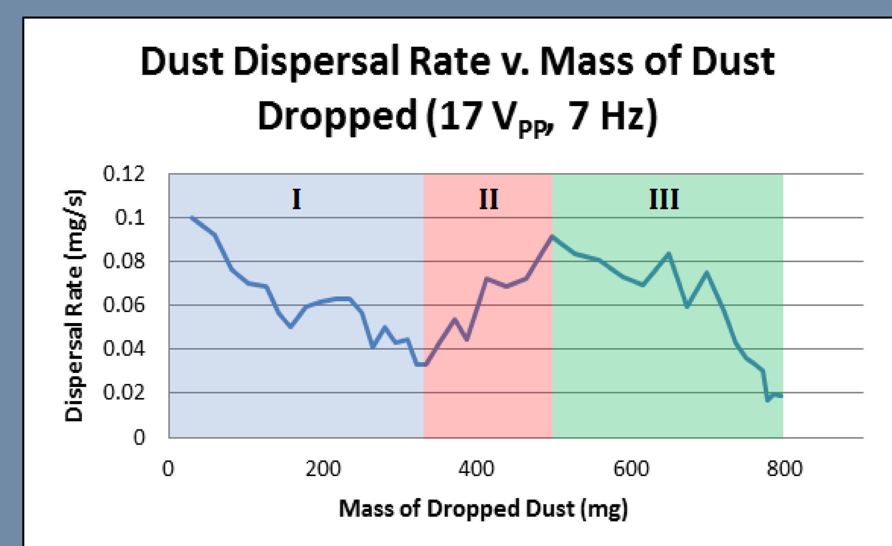

Figure 6. Stage I: Dust compacts around agitator. Stage II: Agitator creates an open space on the mesh. Stage III: Rate decreases as total dust dropped increases.

- Be higher under vacuum (100 mTorr) than at atmosphere (Table 1).

Table 1: Dust Dispersal Rates in Atmosphere and Under Vacuum (9Hz)

Voltage (V_{pp})	Dispersal Rate (mg/s)	Atmosphere or Vacuum
5	0.233	Atm
	0.533	Vac
	0.150	Atm
	0.150	Atm
	0.517	Vac
8	0.467	Atm
	0.467	Atm
	1.000	Vac
	0.717	Atm
	0.450	Atm
	0.400	Atm
	1.230	Vac
	0.783	Atm
	0.360	Atm
	0.316	Atm

Table 1. Dispersal rates for consecutive trials at atmosphere (Atm) and under vacuum (Vac).

Results (continued)

Dust Cloud Formation

Dust clouds form in dusty plasmas when the electrostatic force on the charged dust particles balances the force of gravity (Fig. 7).

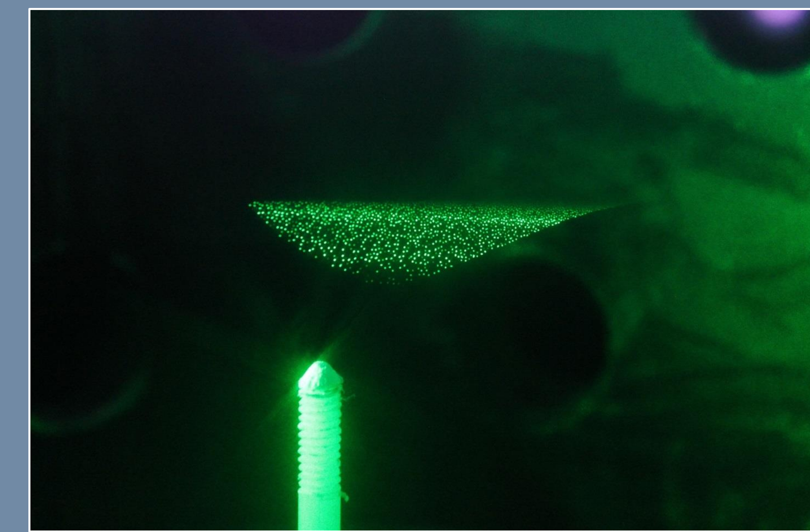

Figure 7. A dust cloud (about 1" wide) forms directly above the POM support (see Fig. 1).

Reproducible dust clouds form for multiple trials over two days (Fig. 8).

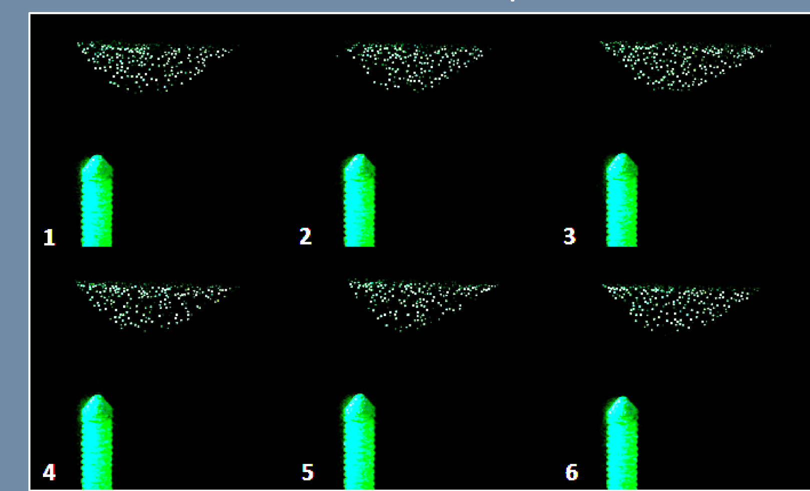

Figure 8. Six trials from day 1 of reproducibility tests.

Conclusion

Although dust dispersal rates are still somewhat unpredictable, this dust dropper can

- Regulate the size of particles and area of dispersion
- Support a wide range of dispersal rates
- Create reproducible dusty plasma environments (clouds) from only dropped dust

Acknowledgments

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