Dust as discharge probe: single and two particle oscillations

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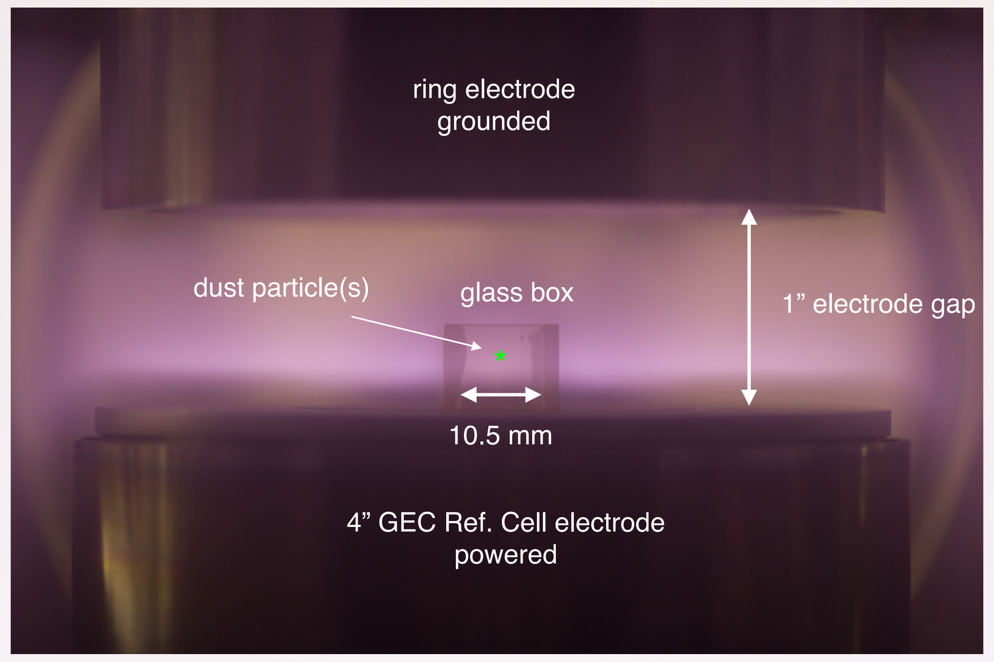
Introduction

The thermally excited oscillation spectra of the smallest possible ensembles of dust particles (one and two grains) levitating in argon RF discharges are analyzed. Single particle oscillations represent the trap-frequency, thus the strength of the electrostatic confinement, while the breathing mode oscillations of two-particle systems are most sensitive to the inter-particle interaction.

The sensitive dependence of these oscillation frequencies on the discharge parameters is investigated in detail.

The experiment

The GEC Reference Cell at Baylor University's Hypervelocity Impacts & Dusty Plasmas Lab. Argon gas in the pressure range of 70 - 200 mTorr was excited with 13.56 MHz RF power signal in the voltage range of 150 - 550 Vpp. The horizontal confinement was enhanced with the application of a 1/2" glass box. Top and side view cameras were used to record image sequences of a few thousand frames at 60 fps.



The theory

The center of mass (or the single particle) in a harmonic trap in the form :

$$V_{\rm tr} = Ar^2$$

results in an oscillation as:

$$M\omega_{\rm tr}^2 = 2A$$

meaning, that measuring the oscillation frequency and knowing the mass results directly the confinement.
If two particles interact with the Yukawa potential:

$$V_{\rm Y} = \frac{Q^2}{4\pi\varepsilon_0}\frac{e^{-r/\lambda}}{r}$$

The Taylor expansion of the total potential around the average inter-particle distance

$$\begin{aligned} V(r)|_{r_0} &= \left(Ar^2 + \frac{Q^2}{4\pi\varepsilon_0}\frac{e^{-r/\lambda}}{r}\right)_{r_0} \approx V(r_0) \\ &+ \left(2Ar_0 - \frac{Q^2}{4\pi\varepsilon_0}\frac{e^{-r_0/\lambda}(\lambda + r_0)}{\lambda r_0^2}\right)(r - r_0) \\ &+ \left(A + \frac{Q^2}{4\pi\varepsilon_0}\frac{e^{-r_0/\lambda}\left(2\lambda^2 + 2\lambda r_0 + r_0^2\right)}{2\lambda^2 r_0^3}\right)(r - r_0)^2 \end{aligned}$$

For the equilibrium distance

$$\frac{Q^2}{4\pi\varepsilon_0} = \frac{2Ar_0^3\lambda}{r_0 + \lambda}e^{r/\lambda}$$

which, substituted into the second order term, gives an equation relating the distance fluctuation frequency to the screening length:

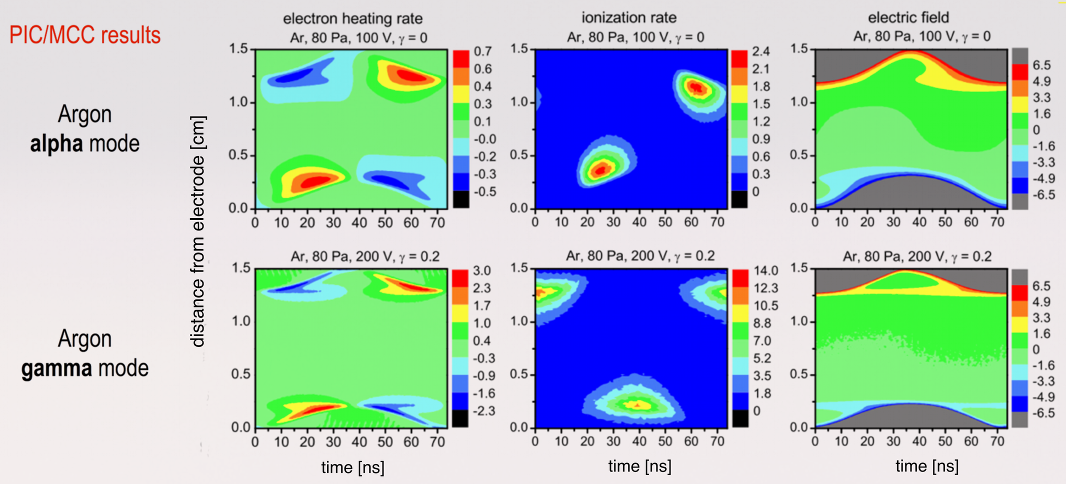
$$\frac{\mu}{2}\omega_{\rm ip}^2 = \frac{A\left(r_0^2 + 3r_0\lambda + 3\lambda^2\right)}{\lambda(r_0 + \lambda)}$$

with $M = 2m$ and $\mu = m/2$.

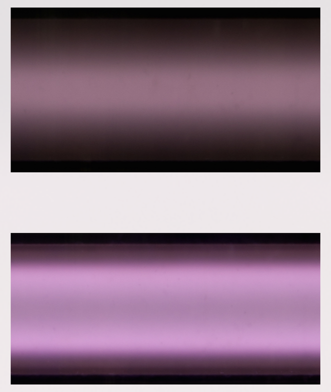
In conclusion: measuring the center-of-mass and inter-particle oscillation frequencies we can compute dust particle charge Q and Debye screening length λ [1].

Background: alpha - gamma operation modes of capacitively coupled RF discharges

Simple (e.g. noble gas, symmetric configuration, non-magnetized, etc.) CCRF glow discharges are known to operate in two regimes, called alpha and gamma modes [2].

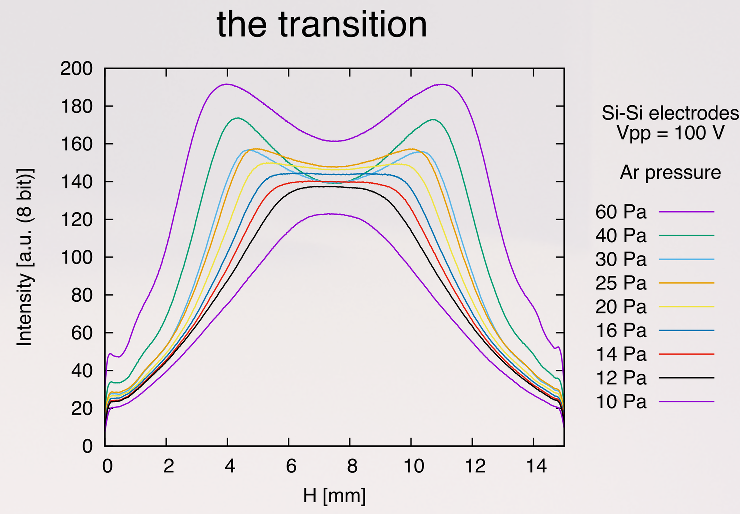


Light emission (photo)



Electrons are accelerated by the expanding sheath, ionization is dominant in the bulk.

Electrons are emitted from the electrode and are accelerated by the sheath. Ionization peaks near the sheath edge.

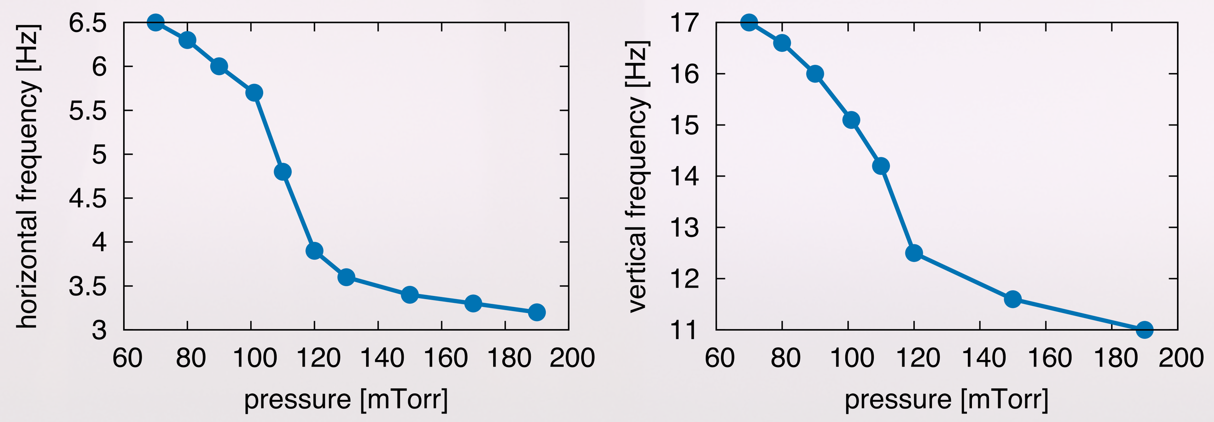


Gamma mode operation, at high pressures and voltages, is very sensitive to the electrode surface conditions (material and cleanliness).
Alpha mode operation, at low pressures and voltages, depends mostly on the gas composition.

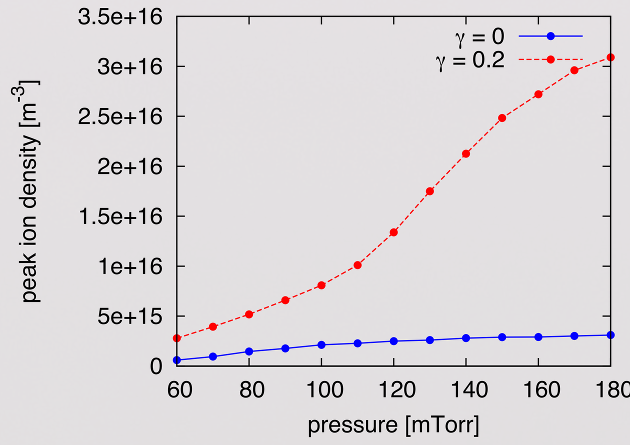
Results

Several experimental campaigns were performed to scan a wide parameter range. Examples:

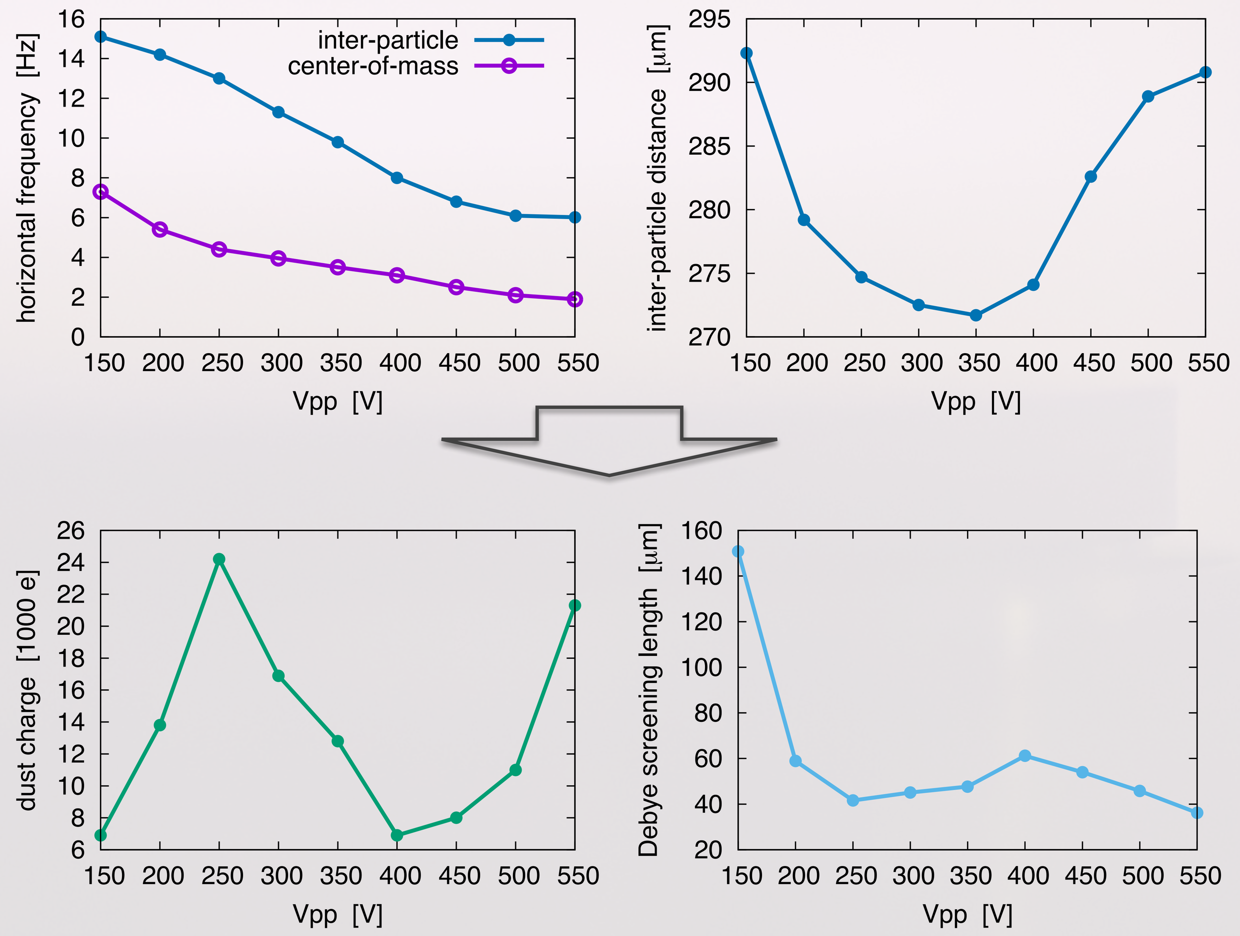
Single 8.9 μm MF particle in Vpp = 480 V ($V_{\textit{self-bias}}$ = -195 V) discharge:



PIC/MCC simulation:
(γ: electron emission yield)



Two 8.9 μm MF particles in p = 150 mTorr discharge:



In conclusion:

- Small dust particle cluster oscillations are very sensitive to the plasma environment.
- Dust particle oscillation frequencies can be used as discharge probes for qualitative and quantitative measurements.
- Both vertical and horizontal oscillations of single dust particles show the alpha - gamma mode transition in CCRF discharges.
- Dust particle charge and Debye screening length can be calculated directly from two-particle oscillation frequencies (sloshing and breathing modes).

References and acknowledgements

[1] M. Bonitz, D. Block, O. Arp, V. Golubnychiy, H. Baumgartner, P. Ludwig, A. Piel, and A. Filinov, *Phys. Rev. Lett.* **96**, 075001 (2006).
[2] T. Hemke, D. Eremin, T. Mussenbrock, A. Derzsi, Z. Donkó, K. Dittmann, J. Meichsner and J. Schulze, *Plasma Sources Sci. Technol.* **22**, 015012 (2013)

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