Advances of Hybrid Kinetic-Fluid Solvers for Gas Discharge Plasmas

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Adaptive Mesh in Phase Space (AMPS) developed in [1] has been applied to simulations of charged particle kinetics in gas discharge plasmas. First results illustrating electron heating mechanism in an RF sheath of Capacitively Coupled Plasmas (CCP) were presented at an Invited talk at the Rarefied Gas Dynamics Symposium [2]. The electron heating involves two steps: gaining directed energy from the electric field, and transforming this energy in collisions with atoms into thermal energy of chaotic motion. In weakly collisional CCP these two steps are separated in space.

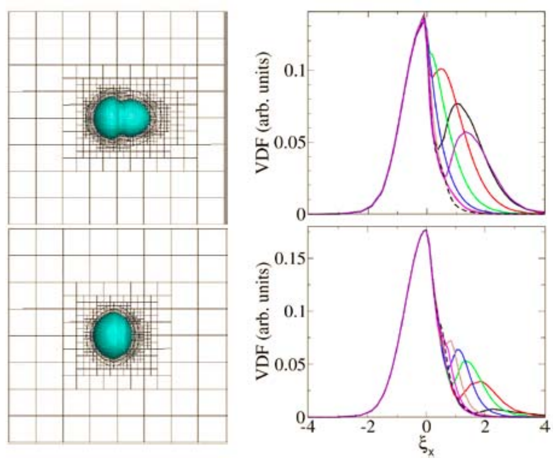


Fig. 1 – Computational mesh and EVDF $f(\xi_x, 0, 0, x, t)$ at the sheath boundary ($x = d$, top) and in the plasma ($x = 3d$, bottom).

An example of the computational mesh in velocity space is shown in Fig. 1 wtih the calculated Electron Velocity Distribution Function (EVDF) at $d\omega / \mathrm{v}_T = 1$, $\lambda / d = 10$, $2eU_0 / (m\mathrm{v}_T^2) = 20$, where d is the sheath width, λ is the electron mean free path, v_T is the mean thermal velocity, U_0 is the potential drop in the sheath, and ω is the field frequency. Electrons are absorbed at the electrode (x=0) during a short time of near-zero electric field, and gain considerable energy being repelled by the moving sheath boundary. The EVDF is highly anisotropic and time-dependent near the plasma-sheath boundary. With increasing distance, oscillations decay, and the EVDF becomes close to isotropic due to electron collisions with atoms. With decreasing ω, substantial time dependence and anisotropy of the EVDF remain during short instants of near-zero electric field when hot electrons escape to the electrode.

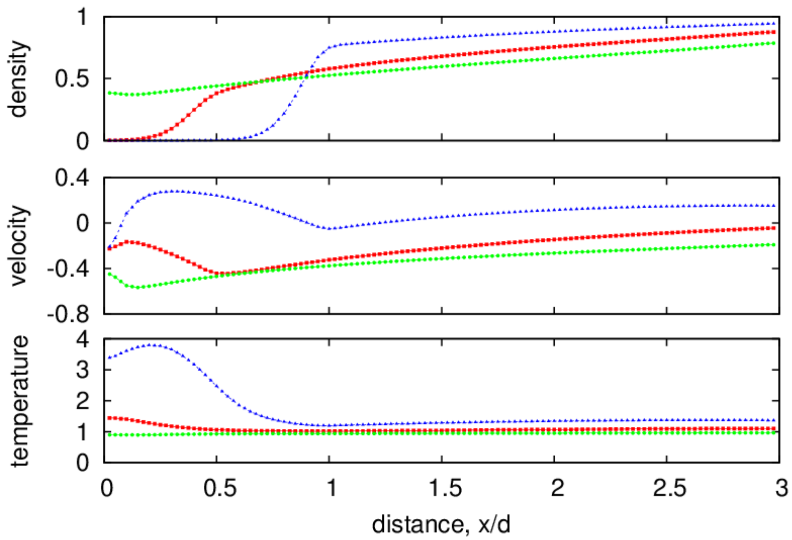
Our Phase I SBIR proposal to DAPRA “Next Generation Plasma Simulation Tool with Adaptive Mesh and Hybrid Kinetic-Fluid Models” was selected for award. The proposed tool will have a) the ability to dynamically switch between fluid and kinetic models, b) robust auto-mesh generation and adaptive mesh refinement algorithms, c) implicit solvers adapted for massively parallel CPU-GPU systems, d) modular structure for easy incorporation of physics sub-models and databases for atomic and materials physics. The project will leverage previous CFDRC work and recent advances of plasma kinetics sponsored by the Plasma Science Center..

References

[1] R.R. Arslanbekov, V.I. Kolobov, and A.A. Frolova, Phys. Rev. E **88** 063301 (2013).
[2] V.I. Kolobov, R.R. Arslanbekov, and A.A. Frolova, AIP Conf. Proc. **1628**, 952 (2014).

ADVANCES IN HYBRID KINETIC-FLUID SOLVERS FOR GAS DISCHARGE PLASMAS

- **Adaptive Mesh in Phase Space (AMPS) applied to study electron heating mechanism in RF sheath of Capacitively Coupled Plasmas.**
- **EVDF is highly anisotropic and time-dependent near plasma-sheath boundary. Oscillations decay, and EVDF becomes close to isotropic in plasma bulk.**
- **Phase I SBIR proposal to DAPRA “Next Generation Plasma Simulation Tool with Adaptive Mesh and Hybrid Kinetic-Fluid Models” selected for award.**

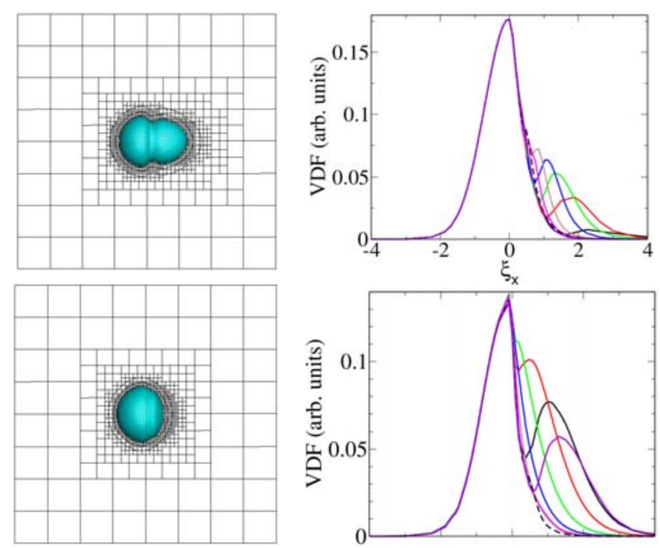


- **Electron density, mean velocity and temperature during rf cycle.**

$$d\omega / v_T = 1$$

$$\lambda / d = 10$$

$$\frac{2eU_0}{mv_T^2} = 20$$



- **Velocity mesh and EVDF**

HIGHLIGHT

CFDRC

Center for Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems

PSC Department of Energy Plasma Science Center

DOE Plasma Science Center
Control of Plasma Kinetics

Temporal Evolution of Electron Energy Probability Function in Dusty Plasmas Measured by Langmuir Probe

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A fundamental understanding of dusty plasma physics is important for the optimization of plasma-aided manufacturing processes. Determination of the electron energy probability function (EEPF) using Langmuir probes is particularly valuable in studying electron-dust interactions. However, Langmuir probe measurements in dusty plasmas are a challenge because particle deposition on the probe leads to contamination and distortion of the measured EEPF. We here present reliable EEPF measurements in a capacitively coupled argon-silane dusty plasma using a shielded Langmuir probe. A solenoid-actuated shield covered the probe which was exposed to the plasma only for short periods of time (less than 6 seconds) when the current-voltage characteristics were recorded during rapid voltage scans. This approach minimized probe contamination.

The evolution of the EEPF in a dusty plasma obtained using this method is shown in Fig. 1. In the presence of dust, the electron density decreased and the electron temperature increased in comparison to a pristine argon plasma. While the population of lower energy electrons decreased in the presence of dust, the high energy tail regions overlapped throughout the experiment.

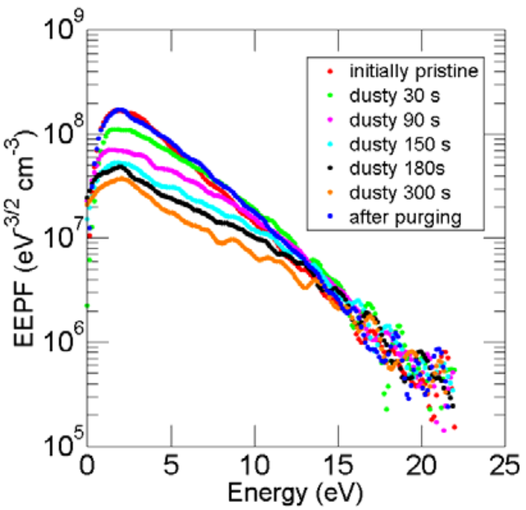


Fig. 1 – Temporal evolution of EEPFs in a 80 mTorr argon-silane dusty plasma

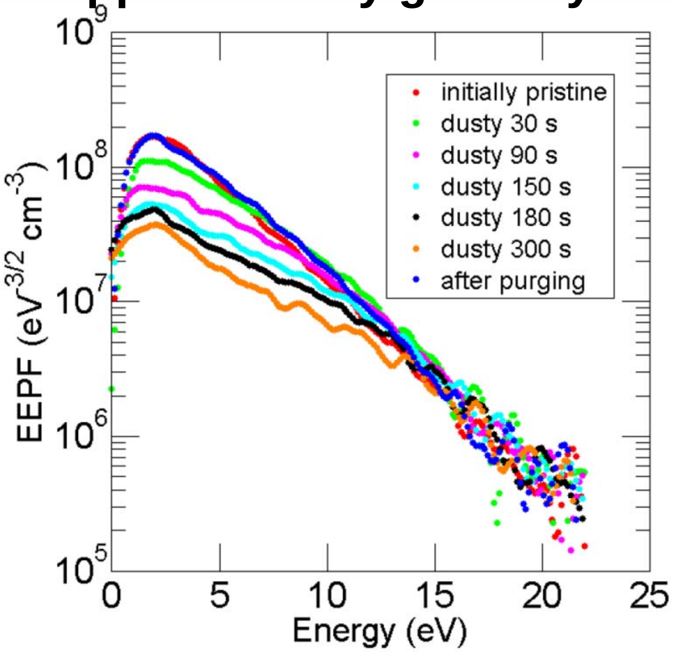
Langmuir probe measurements were complemented with ion density measurements using a capacitive probe [1] and *ex situ* examination of particles using electron microscopy. While the ion density decreased only slightly in the dusty plasma, the electron depletion was significant due to attachment loss to the nanoparticles. Using the ion-electron density difference and the analytical model of particle charging [2], we found that the particle charge was approximately given by one elementary charge per nanometer of particle diameter, and the particle density was on the order of 10^7 cm^{-3}, which was about two orders of magnitude lower than the electron and ion densities in the dusty plasma. Using this technique, we hope to achieve a detailed understanding of the physics of plasma-nanoparticle interactions in dusty plasmas.

References

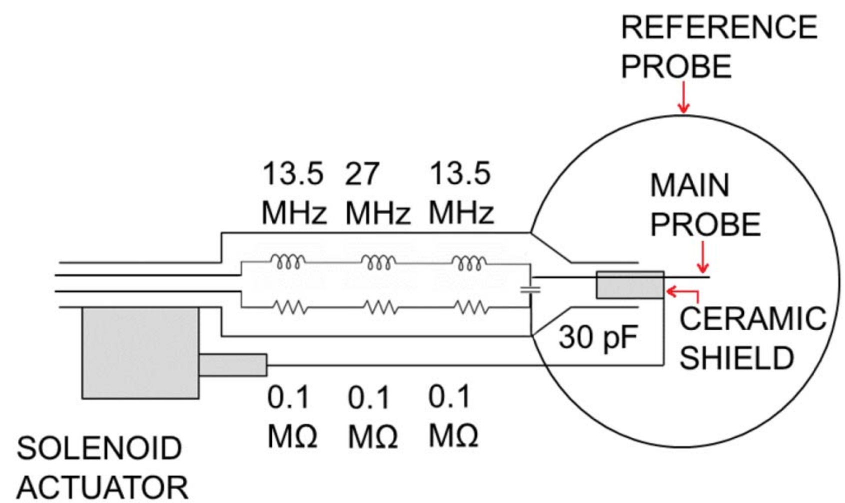
[1] N. Braithwaite, J. Booth and G. Cunge, Plasma Sources and Technology, **5**, 677, (1996).
[2] M. Gatti and U. Kortshagen, Physical Review E, **78**, 046402 (2008).

TEMPORAL EVOLUTION OF EEPF IN DUSTY PLASMA MEASURED BY LANGMUIR PROBE

- Reliable EEPF (electron energy probability function) measurements were made in a dusty plasma for the first time. This is achieved by using a Langmuir probe protected against dust deposition by a solenoid-actuated shield.
- Dusty plasma EEPFs show the depletion of lower-energy electron population and overlapping high energy tails.
- Dust density was ~100 times lower than electron and ion densities. Dust charge was approximately given by one charge per nanometer of diameter.



Temporal Evolution of Dusty Plasma EEPF



Shielded Langmuir Probe