Distribution Functions in Non-Equilibrium Plasmas

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The non-equilibrium character of low-temperature plasmas is exhibited by the form of the distribution functions of free electrons and ions as well as in the population of excited states of atoms and molecules. Strong interactions between particles from different ensembles as well as inhomogeneous and non-stationary electric fields are usually causing the complex forms of non-equilibrium distributions. The talk will show a number of experimental examples ranging from low to atmospheric pressures. The underlying physical mechanisms will be explained, the diagnostic techniques highlighted, and the consequences for application and diagnostics discussed.

1. Introduction

Low-temperature plasmas are characterized by non-equilibrium distribution functions. Generally, the various particle ensembles do not share the same distribution and typically also the particles within an ensemble, especially electrons and ions but also the population of bounded states in neutrals, do not follow thermal distributions, i.e. cannot be described by a Maxwell-Boltzmann equilibrium distribution. This deviation from thermal equilibrium is caused by weak interaction between particles within an ensemble but strong interaction with particles from other ensembles. Further, oscillating and inhomogeneous electric fields on a scale shorter than the charged particle mean free path can have a strong contribution. Consequently, the particular form of the non-equilibrium distributions and the processes causing their formation are at the heart of the physics in these systems. The distributions play a key role for all physical processes, in particular excitation and ionization but also transport properties can be very sensitive.

In this talk a selection of particular non-equilibrium conditions of interest in recent research and application is presented. The underlying physics is explained, the various aspects are illustrated by experimental examples, and the diagnostic techniques are introduced. Recent advances and current challenges are highlighted. Examples will be shown from three general categories.

2. Examples

2.1. Electron Distribution Function

In Radiofrequency discharges the oscillating and spatially inhomogeneous electric field can lead to ballistic electrons and correspondingly strong deviations from simple Maxwellian distribution functions. The related excitation patterns are the basis of spectroscopic access to the spatial-temporal dynamics. In ICP the evanescent electric field penetrating into the plasma can again be imaged by taking advantage of the temporal modulation of the EVDF. Further downstream at sufficiently low pressures, the EEDF becomes non-local which in principle allows determination in the entire volume from a single measurement in the centre. Arrays of smaller ICPs with a clear phase correlation provide an opportunity for a new plasma source based on non-collisional heating of electrons.

2.2. Ion Distribution Function

IVDF in non-equilibrium plasmas generally show show complex profiles which are additionally strongly depending on the particular location in the plasma. Recently it was discovered that in case of charge-exchange dominated transport at low pressures, measurements taken on the wall allow a full spatially resolved reconstruction of the distribution function and basically all plasma parameters, including also the electron density and temperature as well as the ambipolar electric field and potential. While at low pressures the IVDF is effectively one-dimensional, it exhibits a much wider angular distribution at higher pressures. This has consequences not only for the interaction with surfaces but requires also careful interpretation of measurements.

2.3. Bounded Electrons in Atoms and Molecules

The distribution of bounded electrons in non-equilibrium plasmas is usually governed by a balance between collisional excitation and radiative and collisional de-excitation. In the afterglow recombination of cold electrons can lead to an even stronger deviation from thermodynamic equilibrium by population of highly excited Rydberg states. Recently it was discovered that in the afterglow of atmospheric pressure discharges in Helium actually almost all free electrons are converted to Helium Rydberg molecules.