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# Collisionless electron heating in low-pressure discharges

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A key question for all confined plasmas is the coupling of externally supplied electromagnetic power to the free electrons. Closely related is the question about the form of the isotropic part of the electron velocity distribution function which results from the balance of energy gain in the field on one hand and collisional and wall losses on the other hand. Understanding these mechanisms and even being able to model them in a predictive way is central to the further development of plasma sources and processes.

At higher pressures, where the energy relaxation length is much shorter than the system size, both, the heating and the balance of the various processes contributing to the form of the distribution function are local. This is the regime where Ohmic heating is active and local and stationary solutions of the Boltzmann equation can be applied in order to predict the distribution function and calculate transport coefficients and ionization rates for a fluid description of the system.

At low pressures, especially important for instance for semiconductor processing, mean free paths are long and the situation is quite different. There the heating can be non-local and collisionless. Electrons gain on average energy due to the spatial structure of the harmonically oscillating electromagnetic field and not by elastic collisions. Although subsequent isotropization might still be related to elastic collisions, this kind of energy gain is often termed ‘stochastic heating’. Prominent examples are capacitively and inductively coupled plasmas (CCP and ICP) driven by radiofrequency (RF) fields or electron cyclotron resonance (ECR) discharges operating at micro-wave frequencies. A more recent example is the inductively coupled array (INCA) discharge [1-3], also operating in the RF regime, which is based on a novel and externally designed two-dimensional periodic field structure.

Due to the long mean free path, the isotropic distribution function in these plasmas is usually non-local, i.e. it is a function of the total energy only. In contrast to the high pressure case the plasma is now characterized not by a multitude of local distribution functions but by only one effective global distribution function. However, computation of this distribution function is not trivial due to the temporal and spatial structure of the field. For instance 3-D particle-in-cell Monte-Carlo (PIC-MC) simulation including the self-consistent structure of the electromagnetic field is still exceptionally time consuming and challenging.

In this presentation, the basic aspects of Ohmic and collisionless heating will be revisited and selected examples from experiment and simulation will be shown for the plasmas mentioned above. Particular emphasis will be put on the introduction of the novel heating/discharge concept of INCA. A two-dimensional vortex field structure is created by a large array of small planar coils. This structure has well defined resonances in velocity space which lead for mean free paths long compared to the coil size to collisonless heating in the plane of the array. Comparison between experiment and theory shows excellent agreement. Application aspects for large area, low-pressure processing or thruster operation are briefly discussed.

Finally, a novel concept for the fast computation (typically 1 s) of the global isotropic distribution function of the electrons under conditions of stochastic (collisionless) heating will be introduced [4]. In this concept, the 7-dimensional Boltzmann equation describing the spatial-temporal coupling of the electrons to the electromagnetic field is replaced by an effective Fokker-Planck operator that depends only on the absolute velocity. The basic idea is that the interaction of electrons with a spatially localized field can be treated as an effective collision with energy gain. The new operator has a simple form resembling collisional Ohmic heating. This allows easy integration into a standard local Boltzmann solver and fast calculation of the distribution function. Further, particle losses to the wall are explicitly included. The calculations by the LoKI-B code [5] are complimented by an ergodic / Monte-Carlo code which also calculates the global distribution function [6].

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