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Local and Non-Local Electron Heating in Low-Pressure Plasmas

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Power coupling between electromagnetic waves and the plasma electrons is central to the generation of low temperature plasmas. Further, the detailed electron heating mechanism can also influence strongly the form of the isotropic and stationary velocity distribution function. At intermediate or higher pressures, i.e. neutral gas densities, heating is Ohmic and local. However, more interesting and challenging is the lower pressure range, typically below pressures of about 1 Pa, where local power coupling becomes inefficient due to an insufficient number of elastic collisions and correspondingly large mean free paths. In this regime, the natural or a designed spatial inhomogeneity and non-isotropicity of the electromagnetic field offers the opportunity of non-local stochastic, i.e. collisionless, heating.

While the detailed mechanisms can be quite diverse, the basic effect can be broken down to a resonant wave-particle interaction. The simple reason lies in the fact that the wave has an externally defined frequency and a certain spatial structure, which results after Fourier transformation in a superposition of waves. If the thermal motion of an electron coincides accidentally with the phase velocity of one or more of these waves efficient energy gain becomes possible. However, this directional energy gain is not heating yet. Only by elastic collisions isotropization and irreversibility can be provided. The energy gain is usually limited to a small spatial region, where the electromagnetic field has a significant amplitude and the probability for collisions is low, elastic collisions causing isotropization can occur in the entire volume of the plasma. Clearly, this is a non-local warm plasma effect, which can only be described kinetically.

While this general concept is quite obvious, there are in general three challenges:

Firstly, construction of an appropriate kinetic heating operator in order to allow calculation of the electron velocity distribution function.

Secondly, and closely related to the construction of the heating operator, the plasma dispersion relation is dependent on the distribution function itself. Since this is not necessarily a Maxwell distribution, one has to formulate a generalized plasma dispersion function.

Finally, in general the spatial structure of the field, which is at the bottom of the non-local heating, is caused by the complex dispersion of the wave in the plasma. Therefore, external control over the heating is possible only to a very limited extend, e.g. by the choice of the frequency.

In addition, often the effects of local Ohmic and non-local stochastic heating are not clearly separated. In fact, the operation range important for applications is typically characterized by the simultaneous action of both mechanisms.

The heating operator can be derived either from the Boltzmann equation or alternatively from the Fokker-Planck equation. Although the Fokker-Planck equation is usually thought to be describing collisional processes in plasmas, in particular Coulomb collisions, generalization to the field-particle interaction is straightforward. This approach has conceptionally some advantages and provides a clear insight into the underlying physics. Also the problem of deriving a generalized plasma dispersion function for arbitrary distribution functions has been solved. The solution has the additional advantages that the velocity dependence of the elastic collision frequency can be taken into account and the real and imaginary parts are clearly separated even when dissipation is included, i.e. for complex frequencies.

Naturally, not all these aspects can be addressed in detail within the limited time frame of this presentation. Therefore, after a general introduction and a brief outline of the above theoretical aspects, the main focus is put on the classical inductively coupled plasma (ICP) and a recent novel concept of the so called *inductively coupled array discharge* (INCA) [1-4]. The latter provides a designed field pattern and a related wave structure, which is independent of the particular plasma parameters.

A two-dimensional coherent vortex field structure is generated by a large periodic array of small phase-coupled planar coils. This structure has well defined resonances in velocity space which lead for mean free paths long compared to the individual coil size to collisonless energy gain in the plane of the array. It will be shown that this designed in-plane heating mechanism clearly dominates the classical stochastic heating mechanism perpendicular to the plane.

Experimentally the new concept is realized using a driving frequency of 13.56 MHz, coils of 5 cm diameter, and an array of 36 coils (30 cm x 30 cm). Comparison between experiment and theory shows excellent agreement. Interestingly, onset of stochastic heating at sufficiently low pressures (typically $p < 1$ Pa) is associated with a Maxwellization of the distribution function. Operation in noble, molecular and even weakly electro-negative gases performs similarly. Application aspects for large-area, low-pressure processing or thruster operation are briefly discussed.

References

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