Collisional and Non-Collisional Heating in CCPs: A Unified Kinetic Picture

2005 workshop on Nonlocal, Collisionless Electron Transport in Plasmas

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UNIVERSAL BEHAVIOR OF PLASMAS FAR FROM EQUILIBRIUM

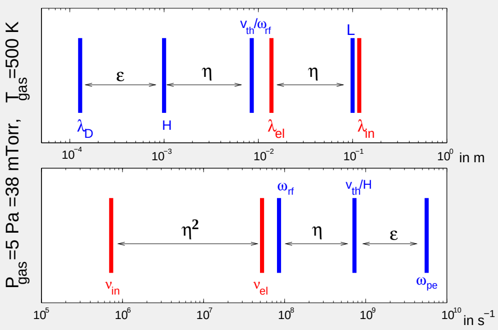
1. Overview

At pressures below 10 Pa, capacitively coupled plasmas exhibit a non-Ohmic mode of power dissipation ("stochastic heating"). Employing methods of asymptotic length and time scale analysis, we derive a self-consistent kinetic electron model for this regime

- Reduced kinetic equation (3d1v) plus boundary conditions
- Ohmic heating appears as a volume term (standard form)
- Novel boundary conditions with *two* different heating terms. (To be identified with *Fermi heating* and *pressure heating*?)

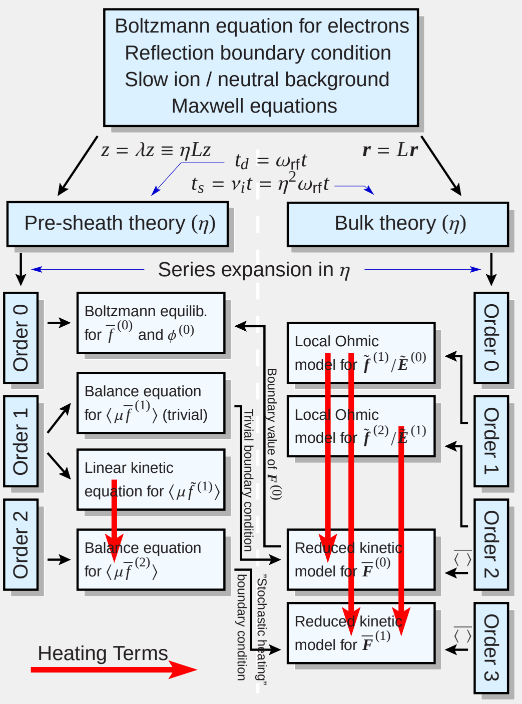
2. Scaling of the Transition Regime

The transition regime ($1\ldots10$ Pa, both heating modes present) is characterized by a pronounced scale separation



- Parameter η is used for asymptotic analysis
- Limit $\epsilon \to 0$ gives quasi-neutrality and hard wall reflection

3. Structure of the Theory



4. The Effective Model

An effective model can be constructed by appropriately adding quantities and equations of first and second order.

- Closed kinetic equation for the EEDF $F \equiv F^{(0)} + \eta F^{(1)}$
- Accurate up to second order in the smallness parameter η
- Ohmic and stochastic heating in a unified formalism

Reduced kinetic equation for the energy distribution $F(t_s, \mathbf{r}, \epsilon)$ (with quasi-neutrality as a constraint)

$$\frac{\partial}{\partial t_s}\left(\sqrt{2\epsilon + 2\Phi}\,F\right) - \frac{\partial}{\partial \epsilon}\left(\sqrt{2\epsilon+2\Phi}\,\frac{\partial \Phi}{\partial t_s} F\right)$$
$$- \nabla\cdot\left(D_v\,\sqrt{2\epsilon+2\Phi}\,\nabla F\right) - \frac{\partial}{\partial \epsilon}\left(D_\epsilon\,\sqrt{2\epsilon+2\Phi}\,\frac{\partial F}{\partial \epsilon}\right) = \sqrt{2\epsilon+2\Phi}\,\langle F\rangle_{\rm in}.$$

The diffusion coefficients are (D_ϵ is Ohmic heating)

$$D_v = \frac{1}{3\nu_m}(2\epsilon + 2\Phi)$$
$$D_\epsilon = \frac{2}{3}(2\epsilon+2\Phi)\sum_{k=1}^{\infty}\frac{\nu_m}{\nu_m^2 + k^2}|\tilde{\boldsymbol{E}}_k|^2$$

The novel boundary condition has only terms of first order in η. It comprises *two* separate energy diffusion terms with coefficients $H_{\rm Fh}$ and $H_{\rm ph}$, respectively, and a (negligible) remainder R,

$$-\boldsymbol{n}\cdot D_v\,\sqrt{2\epsilon+2\Phi}\,\nabla F\Big|_{\partial V} = \eta\left(\frac{\partial}{\partial\epsilon}\left(H_{\rm Fh} + H_{\rm ph}\right)\frac{\partial F}{\partial \epsilon} + R\right).$$

The "Fermi heating" coefficient $H_{\rm Fh}$ reflects the hard wall heating (for those particles who reach it),

$$H_{\rm Fh} = (2\epsilon + 2\phi(0))^{\frac{3}{2}}\,\overline{\frac{ds}{dt}\langle\mu^2\tilde\Psi(0)\rangle}\,\Theta(\epsilon+\phi(0)).$$

The "pressure heating" coefficient $H_{\rm ph}$ is given as an integral over the pre-sheath zone

$$H_{\rm ph} = \lim_{z\to\infty} T_{\rm Fh} - z\frac{\partial}{\partial z}T_{\rm ph}$$
$$T_{\rm ph} = \int_{z^*}^{z}(2\epsilon + 2\phi(z'))\overline{\tilde E(z')\langle\mu\tilde\Psi(z')\rangle}\,dz'$$

The following quantities stem from the pre-sheath model:

- Pre-sheath potential ϕ: Determined by quasi-neutrality
- Reflection coordinate z^*: Zero for particles with $\epsilon > -\phi(0)$, i.e., those which reach the wall. For others $z^* = \phi^{(-1)}(\epsilon)$.
- RF modulated fields $\tilde E_z$ and fluxes $\tilde\Psi$ in the pre-sheath, determined by a non-local transport equation

$$\langle\mu\tilde\Psi_k\rangle(z,\epsilon) = \int_{z^*}^{\infty} G_k(z,z',\epsilon)\,\tilde E_{zk}(z')\,dz'$$

5. Outlook

Directions of future research:

- Verification of the interpretation of the heating terms
- Incorporation of electron wall losses into the theory
- Numerical realization and implementation in a simulator