Energy transfer between electrons and ions in highly ionized plasma

ENERGY TRANSFER BETWEEN ELECTRONS AND IONS IN A HIGHLY IONIZED PLASMA

B. van der Sijde, J. Dielis, B. Pots and D.C. Schram

Physics Department, Eindhoven University of Technology,
Eindhoven, the Netherlands.

Abstract: The energy transfer between electrons and ions has been experimentally determined in a plasma with an ionization degree of 20-90% and an electron temperature of 2.5 - 5 eV. The transfer is within a factor of 2 in agreement with theoretical values. For high current densities sometimes an enhanced energy transfer was found.

Introduction: We reported on energy transfer studies in a highly ionized, low temperature plasma [1]. Quantitative progress has been made in the comparison between experimental and theoretical data [2] of energy transfer between electrons (e) and ions (i) by Coulomb interactions. This transfer is small due to the mass ratio m_e/m_i. Therefore, the ion temperature T_i can be small with respect to the electron temperature T_e due to energy loss to neutral particles, diffusion, heat transport and sometimes impurities. Ion-acoustic turbulence has been proposed as a possibility of anomalous energy-transfer [3]. The comparison between experimental and theoretical values of e-i energy transfer has been carried out for the first time by Dougal and Goldstein [4] with a time-dependent experiment. Their results were in rough agreement with the theory within a scatter of a factor of 3 to both sides. We determined the e-i energy transfer from the local ion energy balance equation in a stationary plasma. The ions gain energy by e-i collisions. The main energy loss is due to ion-neutral (i-n) collisions. The diffusion terms and the contribution of ionization are somewhat smaller, especially for low T_e-values. The method can only be applied succesfully if the ionization degree is high enough ($\alpha > 30\%$) to cause a measurable value of (T_i-T_n). The electron density n_e has to be large enough to ensure a Maxwellian distribution function, but low enough to have a substantial value (T_e-T_i).

Model: We used a plasma with $T_e=(25\text{-}50)10^3$K, $n_e=(2.5\text{-}7)10^{19}m^{-3}$ and a radius r_p of $(1\text{-}2)10^{-2}$m. The relaxation times for e, $\tau_{ee} \approx 6.10^{-9}$ sec and i, $\tau_{ii} \approx 4.10^{-7}$ sec and the energy transfer times are $\tau_{\varepsilon\ ei} \approx 2.10^{-4}$ sec and $\tau_{\varepsilon\ in} \approx 4.10^{-5}$ sec. We consider a small volume element at the axis of the discharge, the dimensions of which are small as compared to the gradient length of the density profile and larger than the mean free path for i-i collisions. If ion-viscosity is neglected, we obtain for the steady state ion energy balance equation:

$$\nabla\cdot(n_i m_i v_d^2/2 + 5\, n_i kT_i/2)\, \underline{v}_d + \nabla\cdot Q = n_i\, e\, \underline{E}\cdot\underline{v}_d + \left(\frac{\partial}{\partial t} n_i \langle \tfrac{1}{2} m_i v_i^2 \rangle\right)_{coll}, \quad (1)$$

where v_i is the ion velocity and $\underline{v}_d$ the ion drift velocity. $\underline{E}$ is the electrical field and $\nabla.Q$ is the heat conduction. This term can be neglected in view of the small ion temperature gradients. The terms with $n_i m_i v_d^2/2$ can be neglected with respect to the $n_i kT_i$ terms since $v_d \ll v_{th}$ (thermal velocity). We didn't account for effects due to plasma rotation and suppose that they are small on the discharge axis. The $\frac{\partial}{\partial t}$ collision term can be distinguished in 1) an e-i term W_{ei}, due to elastic collisions; 2) an i-n term W_{in} due to charge exchange and elastic collisions; 3) an ionization term W_{ion}. Recombination may be neglected. The terms are:

$$W_{ei} = 3/2\ k(T_e-T_i)\cdot n_e\ \frac{8\sqrt{2\pi}\cdot n_i\cdot q^4\cdot \ln\Lambda\cdot m_e^{\frac{1}{2}}}{3(4\pi\ \varepsilon_0)^2(kT_e)^{3/2}\cdot m_i}, \quad (2)$$

where $\ln\Lambda$ is the Coulomb logarithm and q is the elementary charge;

$$W_{in}=3/2\ k(T_i-T_n)\cdot n_i\cdot\frac{4\ n_n}{3\sqrt{\pi}\ m_i}(kT^*)^{\frac{1}{2}}\int_0^\infty E^{*\,2}_{rel}\cdot\exp(-E^*_{rel})\cdot\sigma_m(E)\cdot dE^*_{rel}, \quad (3)$$

where $E^*_{rel} = E_{rel}/kT^*$, $T^*=(T_i+T_n)/2$ and E_{rel} is the relative energy between i and n particles; $\sigma_m(E)$ is the cross-section for momentum transfer. The cross-section for charge exchange $\sigma_{ex}=(6.83-0.78 \log E_{rel})^2 10^{-20}m^2$. See also ref. [5]. By taking into account elastic collisions data of Cramer [6] and the fractional energy-transfer for these collisions, one finds $\sigma_m(E)=1.5\ \sigma_{ex}$. The ionization term is given by:

$$W_{ion} = 3/2\ kT_n\cdot n_e\cdot n_n\cdot\langle\sigma v_e\rangle_{ion}. \quad (4)$$

In this term we took into account direct ionization [7] as well as stepwise ionization via metastable levels [8,9]. The term e $n_i\underline{E}\cdot\underline{v}_d$ in eq. (1) is estimated to be small (20%) with respect to the $\nabla\cdot(5\ n_i kT_i\ \underline{v}_d/2)$ term = W_{tr}. The estimate has carried out with rough $\underline{E}$ and $\underline{v}_d$ values. The influence on the results is small. The agreement between experimental and theoretical data concerning the e-i energy transfer is expressed by a factor f, given by:

$$f = \frac{W_{tr} - W_{in} - W_{ion}}{W_{ei}}. \quad (5)$$

Experiment: The ion and neutral temperatures were determined from Doppler broadening with a Fabry-Perot interferometer. The e-density was determined with Thomson scattering; the e-temperature with the line intensity of a VUV 740 Å argon II line after calibration with Thomson scattering at low current values. The n-density was determined with the intensity of two argon I lines with = 6965 Å and = 7634 Å. This method was calibrated with a plasma condition with T_n=300-400 K, in which case the n-density will be close to the value which corresponds with the filling pressure.

Results and conclusions: In fig. 1 the values of the factor f for four series of measurements are shown. The variation of f is not significant for the series 1 and 2. The systematic increase for the series 3 and 4 at large discharge currents is more significant than the estimate random error of 25% in individual points. When these points are excluded, we find a mean value of f = 0.65 ± 0.05. The agreement with the theory is considered to be satisfactory in view of possible systematic errors, e.g. in the determination of n_n and T_e. The systematic increase of the f-values for the series 3 and 4 may be an indication of anomalous energy transfer, caused e.g. by ion-acoustic turbulence. In fig. 2 we indicated the ratio v_d/v_{th} against the

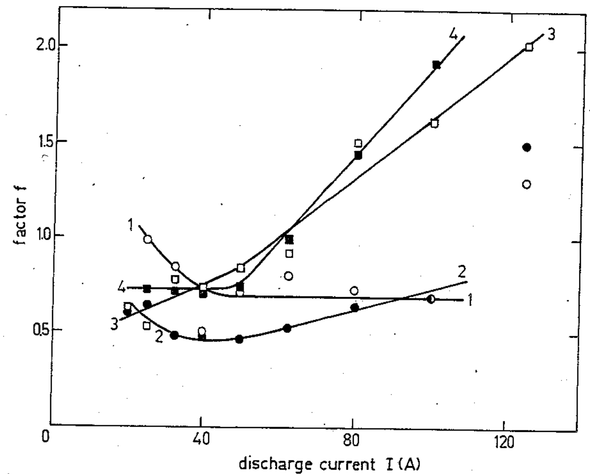

Fig. 1. The value of the factor f, given in eq. 5 as a function of the discharge current for the four series.
○ :1, $B=1.05.10^{-1}T$; p=2.5 mtorr; ●:2 $B=1.5\cdot10^{-1}T$, p=2.5 mtorr.
□ :3, $B=0.6\cdot10^{-1}T$; p=2.5 mtorr; ■:4 $B=1.5\cdot10^{-1}T$, p=1.5 mtorr.

ratio T_e/T_i together with the stability criterion for ion acousticturbulence [10]. It appears that the curve of series 3 coincides fairly well with this criterion, whereas the curves of series 1 and 2 are situated in the stable region, in good agreement with the f-values. The curve of series 4 doesnot fit well. However, there is an indication from the voltage measurements that the drift velocities for series 4 are estimated too low. It seems that the ratio T_e/T_i is established at such values that the ratio v_d/v_{th} remains close to the stability criterion. This establishment may be caused by additional energy transfer. In ref. [11] it is argued that in a steady state plasma the stationary ion acoustic turbulence will be close to the thermal level. However, this conclusion is based on a collisionless plasma model in which substantial deviations from the Maxwellian distribution for ions occur. These deviations are not likely to be large in the investigated plasma as a consequence of the high i-i collision frequency.

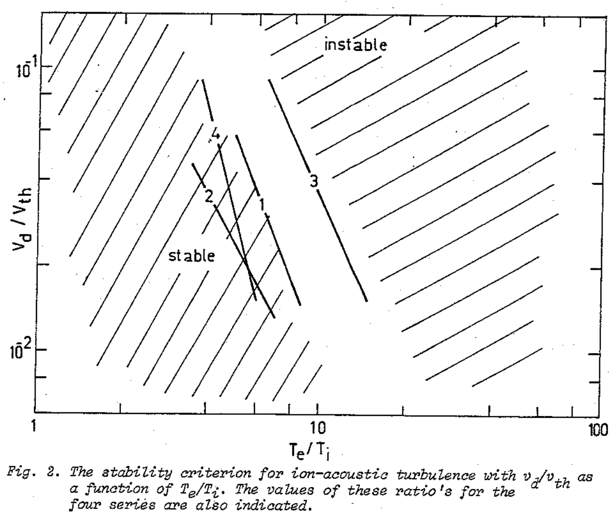

Fig. 2. The stability criterion for ion-acoustic turbulence with v_d/v_{th} as a function of T_e/T_i. The values of these ratio's for the four series are also indicated.

References:

[1] Van der Sijde, B., Bull.Am.Phys.Soc. 19(1974)162.
[2] Spitzer, Jr., L., Physics of fully ionized gases, Inters.Publ.Inc.N.Y. (1956).
[3] Schrijver, H.et al.,Paper IAEA-CN 33/c3-1, 5th Intern.Conf.Plasma Phys. Contr.Nucl.Fusion Res. Tokyo, 1974.
[4] Dougal, A.A. and Goldstein, L., Phys.Rev. 109(1958)615.
[5] Appert, K., Phys.Letters 32A(1970)477.
[6] Cramer, W.H., J.Chem.Phys. 30(1959)641.
[7] Laborie, P., Rocard, J.M. and Rees, J.A., Electr. cross-sections and macrosc.coeff. Dunod,Paris (1968).
[8] Mc.Conkey, J.W. and Donaldson, F.G., Can.J.Phys.51(1973)914.
[9] Dixon, A.J.et al.,Abstracts VIIth ICPEAC, Beograd 1973, p.405.
[10] Fried, B.D. and Gould, R.W., Phys.Fluids 4(1961)139.
[11] Dum, C.T.et al.,Phys.Rev.Letters 32(1974)1231.