

Anomalous Ion Heating and Thermal Energy Transport

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Abstract: The enhanced ion heating, resulting from current driven modes at about the ion plasma frequency when a fraction of the electron population is trapped and the circulating electron distribution tends to runaway as a whole, is treated and compared with the experimental observations. A new dissipative trapped ion mode driven by the impurity density gradient is found and shown to produce outflow (decontamination) of impurities but also enhanced ion thermal conductivity.

1. Current driven modes with $\omega/k_{\parallel} > (\Delta B/B)^{1/2} v_{the}$ can be excited in regimes where a fraction $(\Delta B/B)^{1/2}$ of the electron population is trapped and the applied electric field is such that the circulating electron distribution tends to runaway as a whole (slide-away regime) [1]. The relevant modes are electrostatic, with potential $\tilde{\phi} = \tilde{\phi}_k \exp(-i\omega t + ik_{\perp} r_{\perp} + ik_{\parallel} l)$ and are treated in a simplified geometry where l indicates a distance along a magnetic field line. We consider the frequency range $\Omega_i < \omega < \Omega_e$, $\Omega_j = eB/(cm_j)$ being the gyrofrequency of species j , and transverse wavelengths such that $\rho_i^{-1} < k_{\perp} < \rho_e^{-1}$, where $\rho_j \equiv v_{thj}/\Omega_j$. Therefore the ions can be treated as unmagnetized and the relevant wave-particle resonances are of the form

$$k_{\perp} v_{\perp i} + k_{\parallel} v_{\parallel i} = \omega = k_{\parallel} v_{\parallel e}$$

Since the region of positive slope in the electron distribution is produced by the circulating electrons $v_{\parallel e} \gtrsim (\Delta B/B)^{1/2} v_{the}$, effective ion heating can be produced only if $v_{\perp i} \sim v_{thi}$. Therefore $k_{\perp}/k_{\parallel} \gtrsim (\Delta B/B)^{1/2} (v_{the}/v_{thi})$ and longitudinal energy of the current carrying electrons is transferred mostly as transverse energy to the ions. The transverse momentum in the electron-wave resonance is taken up by the magnetic field while the longitudinal momentum exchanged between circulating electrons and ions prevents the first population from running away and produces a finite resistivity. Considering the electron distribution as composed by two Maxwellians in the longitudinal direction, the relevant dispersion relation can be written as

$$k^2 \lambda_{De}^2 = (T_e/T_i) W(\omega/kv_{thi}) + (n_i/n) W(\omega - k_{\parallel} u_i / k_{\parallel} v_{the}) + [n_o T_e / (n T_{eo})] W(\omega/k_{\parallel} v_{theo})$$

where λ_{De} is the electron Debye length, the subscript 1 refers to circulating electrons and zero to trapped electrons, and W is the well known Landau integral. We can see that the solution of this equation for ω real has two branches, one roughly corresponding to ω_{pi} , the ion plasma frequency, and the other to $k_{\parallel} \omega_{pe}/k$. The lower branch has a lower threshold, as measured by $\xi = u_e/v_{the}$ where $u_e = J/(ne)$ is the total electron drift velocity. A quasilinear analysis of the effects of these modes has been carried out and correlated with the onset of fluctuations, observed in plasmas produced by the Alcator device, and of sharp ion heating as $\langle \xi \rangle$, an average taken over the plasma cross section, becomes larger than a critical value. The observed spectrum is sharply peaked around ω_{pi} in the range 350 ÷ 700 MHz and has been seen to extend up to 4GHz.

The analysis of electron-loss cone modes, in order to explain the

enhanced emission, over the thermal level, of electron cyclotron radiation has also been carried out. [2]

2. We have found a new mode, in the trapped ion regime, that is standing along the magnetic field lines, has odd electrostatic potential around the point of minimum field, and whose growth rate depends on the collision frequency of trapped ions and on the density gradient of the impurity population. This is of the order of

$$\gamma \sim \left(\frac{L}{\lambda_{ieff}} \right)^{1/2} \frac{v_{thi}}{r_{nI}} \left(\frac{L}{r_n} \right) (k_{\perp} \rho_i)^2 \frac{Z_{eff}}{Z}$$

where L is the magnetic field periodicity length, $\lambda_{ieff} = (v_{thi}/v_i) (\Delta B/B)^{3/2}$ the effective mean free path of trapped ions, r_n and r_{nI} the density gradient scale distance for the main ions and impurity ions respectively, Z and Z_{eff} the impurity and the plasma effective charge number respectively. The considered mode is unstable if impurities are accumulated at the center of the plasma column, so that $d \ln n_i / d \ln n_j > 0$ if

$$\frac{d \ln T_i}{dr} \left(\frac{d \ln n_i}{dr} \right)^{-1} > \frac{2}{3}$$

Thus the instability produces an outflow of impurities (decontamination) [3], for a typical relative temperature gradient that is more realistic and smaller than that predicted by the collisional transport theory. In particular, for values of the actual ion temperature gradient between the two critical temperature gradients, we can have a situation in which the impurities are concentrated at the outside of the column, with the collisional inward impurity flux balanced by the outward impurity flux due to the impurity-driven modes. At the same time anomalous ion thermal energy transport is produced but this occurs at a slower rate than that for impurity particle transport. [4]

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 Vol. I