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Conditions for anomalous energy and momentum transfer from electrons to ions in ECCD discharges on TCV

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Experimental evidence of the anomalous acceleration of ions in the TCV tokamak in regimes with second-harmonic (X2) Electron-Cyclotron Current Drive (ECCD) in low current, low density, high temperature discharges is reported in a companion paper presented at this conference [1]. This text concentrates on the presentation of a possible mechanism explaining the observed phenomenon.

The temperatures of suprathermal tails in the ion distribution function, experimentally observed with TCV's Neutral Particle Analysers (NPA) [2], measuring charge exchange neutral fluxes perpendicularly to the magnetic field, show a strong correlation with the suprathermal electron dynamics. Figure 1 shows the rapid and correlated time evolution of the measured suprathermal electron (perpendicular X-mode ECE) and ion temperatures (compact NPA) when ECCD is switched on and resonant at the magnetic axis.

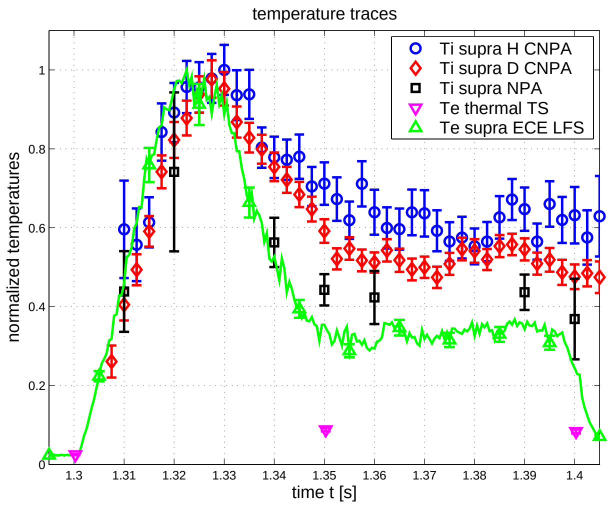

Figure 1: Correlation of electron and ion temperatures (normalized) with ECCD injection. At t=1.3 s, 3 X2 gyrotrons start deposition of 1.5 MW of microwave power, one in ECH, two in counter-ECCD configuration.

The very short timescales for the appearance of these ions cannot result from simple Coulomb collisions and suggest a wave-particle interaction, able to resonate with the electrons and ions simultaneously. A possible candidate is the current-driven ion-acoustic instability, excited in plasmas with drifting electrons (the onset threshold depends on large T_e/T_i), propagates at frequencies $\lesssim \omega_{pi}$ and can transfer parallel momentum and energy from the electrons into mostly transverse energy of the ions [3].

ECCD launching angle, electron density and current scans presented in [1] are qualitatively in agreement with the predictions of the theory: Whereas the bulk temperatures ($T_e^{(0)}$, $T_i^{(0)}$), through collisions, slightly increase with electron density, the number of suprathermal electrons and ions decrease due to the reduced electron drift velocity (decreasing ECCD efficiency). The same tendency is seen in the ϕ_{ECCD} scan; the tail is most populated when the driven current is highest (maximum drift velocity). On the other hand, with increasing inductive current, the toroidal electric field is found to fall, implying decreased resistivity! Simultaneously, the energy and density of the suprathermal ion populations are observed to be strongly decreased, which is, in the frame of the theory, understood as a loss of anomalous resistivity due to reduced momentum transfer from electrons to ions.

In the following, it is shown that ion-acoustic turbulence can, in principle, develop in the plasmas with our parameters.

Conditions for the onset of the instability

For the sake of simplicity, the plasma particle populations are described by maxwellian distribution functions: a) a thermal electron bulk denoted by $f_e^{(0)}$; b) a shifted suprathermal electron

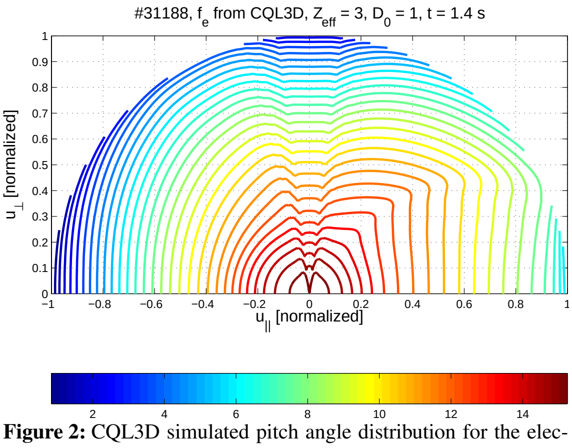

Figure 2: CQL3D simulated pitch angle distribution for the electrons.

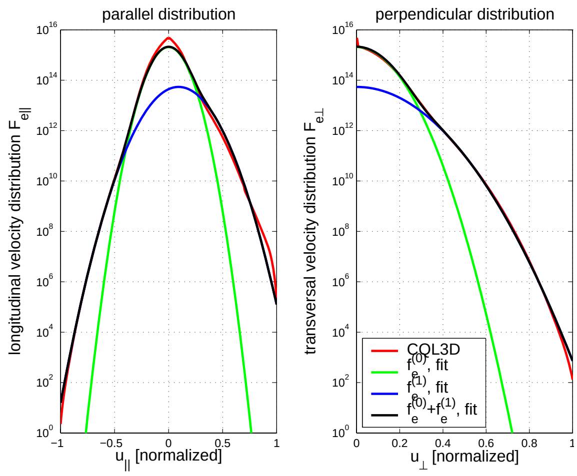

Figure 3: 2D-fit of the electron distribution using two anisotropic maxwellians, one with parallel drift.

population with a modest drift velocity parallel to the magnetic field compatible with the current driven by ECCD and high perpendicular temperature due to electron-cyclotron (pure perpendicular ECH) power deposition ($f_e^{(1)}$). c) Ions (fuel gas and impurities) are initially considered as isotropic ($f_i^{(0)}$). The ratio of electron to ion temperature is high, for the electrons we distinguish between temperatures perpendicular and parallel to the magnetic field (anisotropy parameter τ). We consider deuterium plasmas with a small fraction of carbon impurities, with effective charge Z_{eff} in the range 2,..,3. The setup of the electrons of a plasma of interest (discharge with internal transport barrier, 1 MW on axis counter-ECCD, 1 MW off axis to achieve high temperature and to sustain the ITB) was simulated with the Fokker-Planck code CQL3D [4] (see figure 2). The approximate description with the set of Maxwellians is parameterised by $Te^{(0)} = 7$ keV (consistent with Thomson scattering), $Te_{\|}^{(1)} \simeq Te_{\perp}^{(1)} = 15..20$ keV, $n_e^{(0)}(\rho = 0) \sim 2 \cdot 10^{19} m^{-3}$ (from inverted FIR interferometry data), $n_e^{(1)}/n_e^{(0)} \approx 0.1$, $v_d^{(1)} \approx 0.7 v_{the\|}^{(1)}$, consistent with the driven current density $J_{CD} = e n_e^{(1)} v_d^{(1)} \lesssim 10\ MA/m^2$. The bulk ion temperature is about 300 eV (CXRS), consistent with the thermal part of the NPA charge exchange spectrum.

The relevant linear dispersion relation for an electrostatic wave ($\Omega_{ci} \ll \omega \ll \Omega_{ce}$) for a magnetised plasma may be written

$$\varepsilon(\mathbf{k},\omega) = 1 + \sum_{\alpha} \frac{\omega_{p\alpha}^2}{k^2 v_{th\alpha\|}^2} \sum_{n=-\infty}^{\infty} \Lambda_n(\beta_\alpha) \left\{ 1 + \frac{\omega + (\tau_\alpha - 1) n \Omega_\alpha}{\omega - n\Omega_\alpha} \left[W\left(z_n^{(\alpha)}\right) - 1 \right] \right\} = 0 \qquad (1)$$

with $\omega_{p\alpha}$ the plasma frequency of population α, $v_{th\alpha\|}$ the thermal velocity parallel to the magnetic field, $\Lambda_n(\beta_\alpha) = e^{-\beta} I_n(\beta)$ with $I_n(x)$ a modified Bessel function of the first kind and $\beta = k_\perp^2 \rho_\alpha^2$ with ρ_α the mean Larmor radius. The argument of the dielectric function $W(z)$ is $z_n^{(\alpha)} = \frac{\omega - k_\| v_{d\alpha} - n\Omega_\alpha}{|k_\|| v_{th\alpha\|}}$.

The ions are treated unmagnetised since the resonance at Ω_{ci} is not present. For magnetic fields $B = \sim 1.2$ T, $\omega_{pe} \approx |\Omega_{ce}|$, Doppler interactions ($n = \pm 1$) are unimportant and only the Čerenkov interactions are considered. The argument of the dispersion function is convergent for the electrons ($|z| \ll 1$) and asymptotic for the ions; terms to fourth order in z were retained. With these simplifications, we search for a solution $\omega = \omega_\mathbf{k} + i\gamma_\mathbf{k}$ with $|\gamma_\mathbf{k}| \ll |\gamma_\mathbf{k}|$. The frequency of the mode is

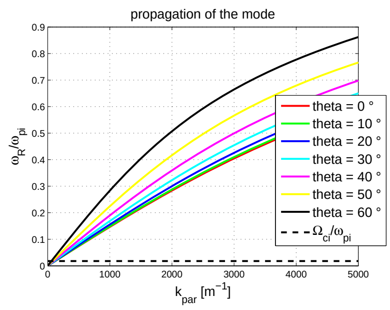

Figure 4: Solution of $\Re\varepsilon(\mathbf{k},\omega) = 0$ for different propagation angles with respect to the direction of the magnetic field.

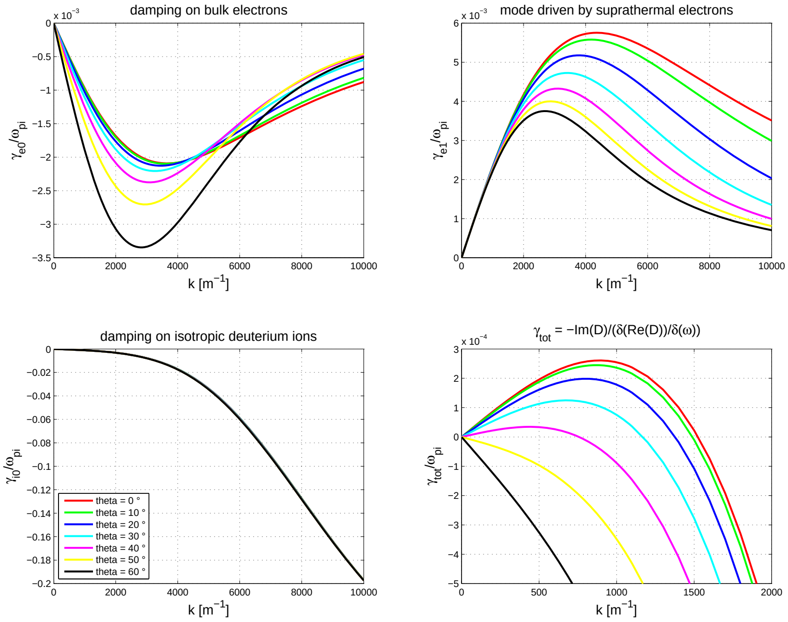

Figure 5: γ_α: from left top to right bottom: electron bulk, drifted hot electrons, deuterium ions and total growth rate.

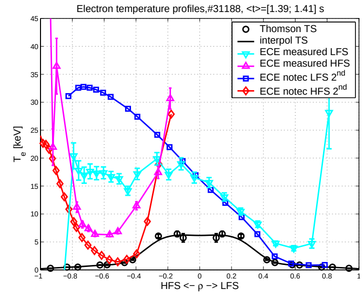

Figure 6: Simulation of ECE with *NOTEC*.

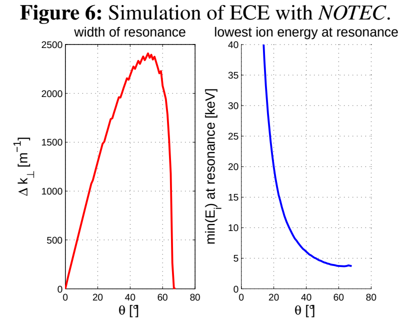

Figure 7: Angular dependence of the resonance. Left plot: width of the spread of perpendicular wave numbers at resonance. Right plot: Minimum energy of ions at resonance.

obtained from $\Re\varepsilon(\mathbf{k},\omega) = 0$ by solving equation 1 numerically. For wave numbers $1/\rho_i \ll k \ll 1/\rho_e \approx 400..4000\ \mathrm{m}^{-1}$, where this theory applies, a solution exists with $\omega_\mathbf{k} \lesssim \omega_{pi}$, figure 4. In the resonant approximation, the rate of change of the amplitude of the instability is $\gamma_\mathbf{k} = -\left.\frac{\Im\varepsilon(\mathbf{k},\omega)}{\Re\frac{\delta\varepsilon(\mathbf{k},\omega)}{\delta\omega}}\right|_{\omega=\omega_\mathbf{k}}$, whose contribution due to the different plasma populations is shown in figure 5 (normalized to ω_{pi}).

The parameters used in the calculation are those fitted to the CQL3D distribution function for discharge #31188 at t = 1.4 s, for different propagation angles θ with respect to the direction of the magnetic field $\mathbf{B}$. As the ions (deuterium is shown here) were assumed to be distributed isotropically, Landau damping (γ_{i0} is negative) is independent of θ, but is most efficient at high $|\mathbf{k}|$. This calculation was performed with Z_{eff} = 2.5 and damping on carbon may be neglected. The growth rate of the instability, given by positive γ_{e1}, is maximum for alignment of $\mathbf{k}$ with $\mathbf{B}$. Following [3] we argue that the wave picks up parallel momentum and energy and is then damped on a large angular spread on the ions. The relevant resonance condition may be written

$$\mathbf{k}\cdot\mathbf{v_i} = \omega = k_\parallel v_{e1\parallel} \tag{2}$$

indicating that, for $k_\perp > k_\parallel$, longitudinal electron energy is transferred into mostly transverse energy of the ions. However, Landau damping may be efficient on the bulk of the electrons, indeed, γ_{e0} becomes strongly negative with increasing θ. The total $\gamma = \sum_\alpha \gamma_\alpha$ drops below zero for large $|\mathbf{k}|$ due to the strong ion damping and doesn't excite the mode for $\mathbf{k}$ when $\theta > 50°$.
The radiative Electron Cyclotron Emission (ECE) perpendicular temperature determined from measurements of radiometers working in X-mode with antennaes at HFS and LFS at the midplane gives much higher values (up to 35 keV) than those obtained from the estimations with CQL3D. Simulations of the ECE spectra with the 3D ray tracing code *NOTEC* [6] indicated an increased density of suprathermal electrons ($n_e^{(1)}/n_e^{(0)}$ = 0.2), diffusing to radii up to $\rho \simeq 0.4$ (figure 6). Increasing $n_e^{(1)}/n_e^{(0)}$ (with the drift velocity corrected to maintain the level of current drive) and the anisotropy $T_{e\perp}^{(1)}/T_{e\parallel}^{(1)}$ increases the spread of k-vectors to $\theta > 60°$.

From the resonance condition, equation 2, assuming $v_{e\|}^{(1)} \approx v_{the\|}^{(1)}$, the range of resonant ion velocities may be determined. Figure 7 shows the angular dependence of the resonant velocity for the parameters as estimated by *NOTEC*, where a minimum is observed at $\theta = 63°$ corresponding to a deuterium ion energy of 3.2 keV (5 times the thermal ion velocity), where the ion density is about 6 orders of magnitude lower than $n_i^{(0)}$. As the tail develops, we may assume the damping on the ions must be strongly increasing. For a weak tail population, our linear model may be hopefully used to extrapolate this effect. The addition of a maxwellian suprathermal ion population to equation 1 shows that with a small fraction $n_i^{(1)}/n_i^{(0)}$ the ion damping strongly increases and the number of ions involved in the resonance become important.

Quasilinear estimates

Work is currently in progress, to solve the quasilinear diffusion equation at marginal stability with a (varying) external electric field in order to maintain the inductive current (#31188: I_p = 140 kA, $\mathbf{E}_T$ = -0.05 V/m). In our scenario, the electric field **E**, and the imposed ECCD, continuously drive the instability. The **E**-field accelerates a small number of electrons to runaway velocities, which we observe through (weak) signals on a hard-X ray detector outside the torus. For discharge #31188 discussed here, the Monte-Carlo code DOUBLE interpolates the NPA CX spectrum using a bi-maxwellian function and estimates a fraction of 10 % of the ions being located in the tail, figure 8 (a constant profile of suprathermal ions is assumed for $\rho \lesssim 0.7$). The effective tail temperature is $T_i^{(1)}$ = 2.4 keV, obtained from the NPA ion energy distribution slope. The observed steady-state tails on the ion distribution function may be understood as the saturation level of the resonant process, the transfer of electron momentum to the ions results in anomalous resistivity, which prevents the electron distribution from running away as a whole (the so called slide-away regime [3]).

However, without solving the quasilinear diffusion equation, we may consider the instability as trying to establish a quasilinear plateau in the distribution function. For the gentle bump instability [5], the energy density in the wave to be dissipated on the resonant particles may be approximated by $\frac{1}{2}n_e^{(1)} m_e v_d^{(1)} v_{th1\|}$, which is of the order of the energy required to bring the resonant ions into the tail (obtained from the difference in the energy of the ions in the thermal and suprathermal population above the knee energy, $E \simeq 1.6$ keV, measured by the NPA charge-exchange spectrum).

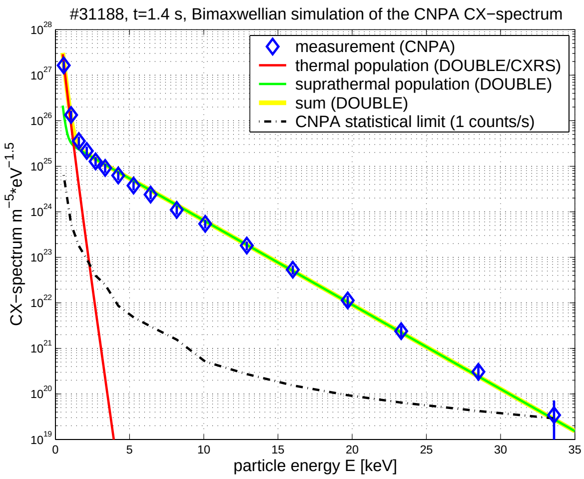

Figure 8: Compact NPA CX spectrum and DOUBLE simulation. $n_i^{(1)}/n_i^{(0)}$ = 0.1, $T_i^{(0)}$ = 300 eV, $T_i^{(1)}$ = 2.4 keV, E_{knee} = 1.6 keV.

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