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

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Ch. Schlatter, B. P. Duval, A. N. Karpushov, E. Asp, S. Coda, V. S. Udintsev `christian.schlatter@epfl.ch`

Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas,
Association Euratom-Confédération Suisse, CH-1015 Lausanne, Switzerland

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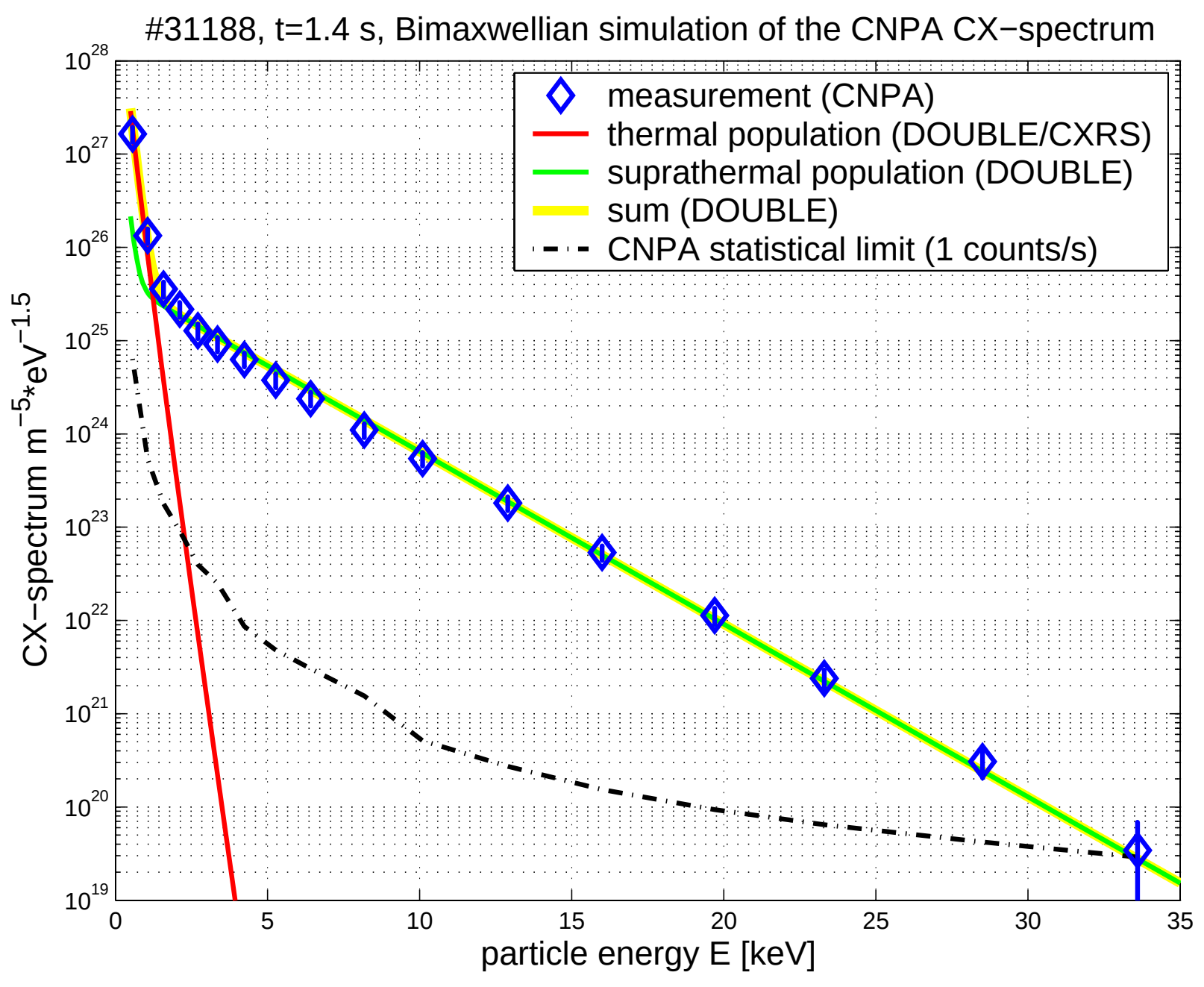
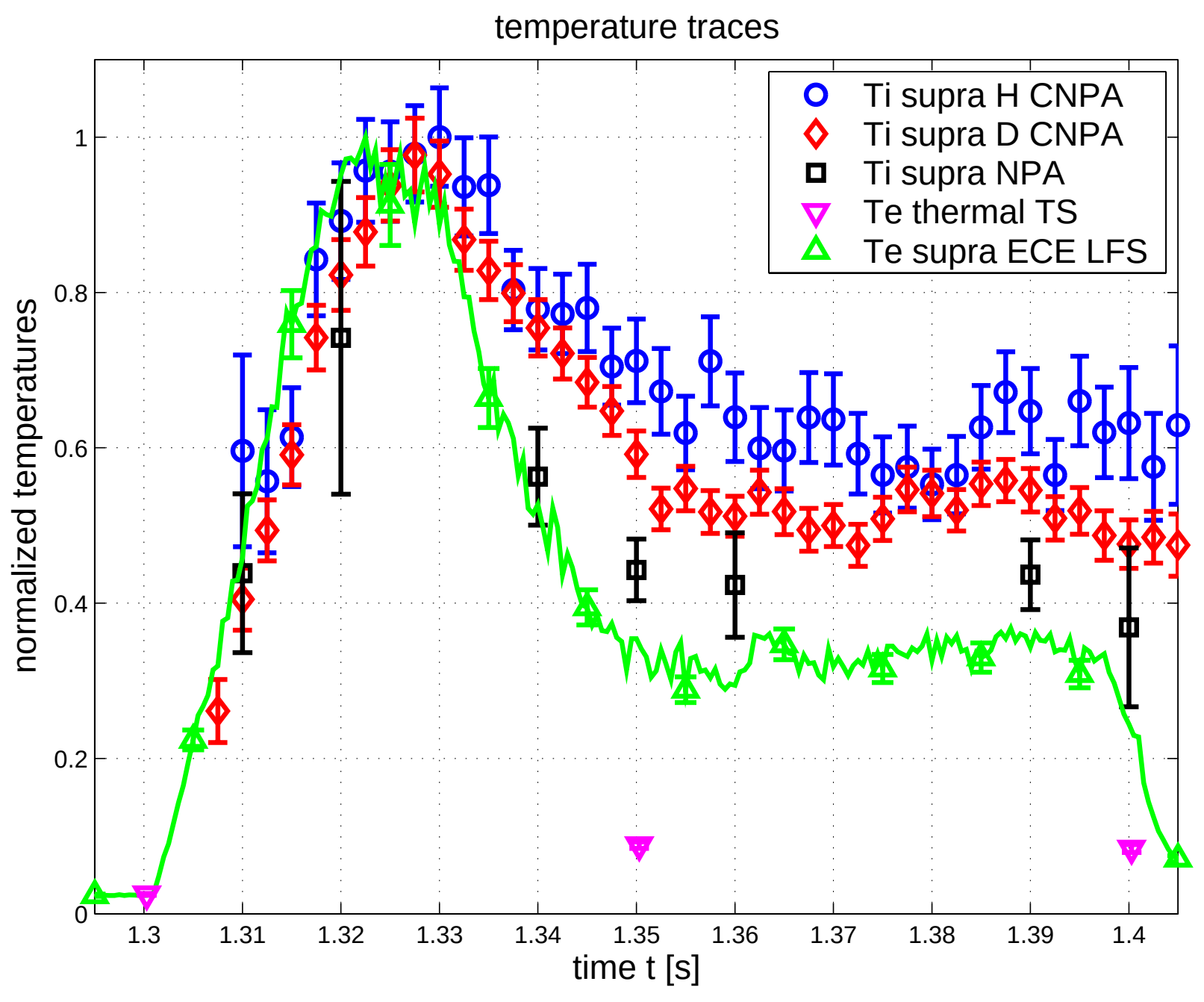
Experimental evidence of suprathermal tails in f_i

- suprathermal tails on ion distribution function are observed in TCV discharges with second-harmonic (X2) Electron-Cyclotron Current Drive (ECCD) at low current, low density, high electron temperature.
- observation with vertical NPA and horizontal CNPA, both looking ⊥ to the magnetic field.
- an overview on the experimental evidence of suprathermal tails is given on Alexander Karpushov's poster P1.152
- the figure shows the compact NPA CX spectrum and its simulation with the Monte Carlo code DOUBLE-TCV for discharge #31188 with internal transport barrier. $n_i^{(1)}/n_i^{(0)}$ = 0.1, $T_i^{(0)}$ = 300 eV, $T_i^{(1)}$ = 2.4 keV, E_{knee} = 1.6 keV, t = 1.4 s, Z_{eff} = 3.



Strong anomalous ion heating on short time scales

- the tail formation is much faster than what Coulomb collisions predict.
- the time scales suggest the presence of a resonant wave-particle interaction.
- the figure shows the normalized time evolution of electron (ECE) and ion temperature (CNPA) when on-axis ECCD is switched on 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.



Resonant wave particle interaction, with both e and i

- Current-driven ion-acoustic instability can resonate with electrons and ions and can transfer momentum and energy from electrons to ions [3].
- Relevant dispersion relation in a magnetized plasma ($\alpha \in \{e, H, D, C\}$):

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

where $\Lambda_n(\beta_\alpha) = e^{-\beta} I_n(\beta)$ with $I_n(x)$ the modified Bessel function of 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

$$z_n^{(\alpha)} = \frac{\omega - k_\| v_{d\alpha} - n\Omega_\alpha}{|\, k_\| \,|\, v_{th\alpha\|}}. \qquad (2)$$

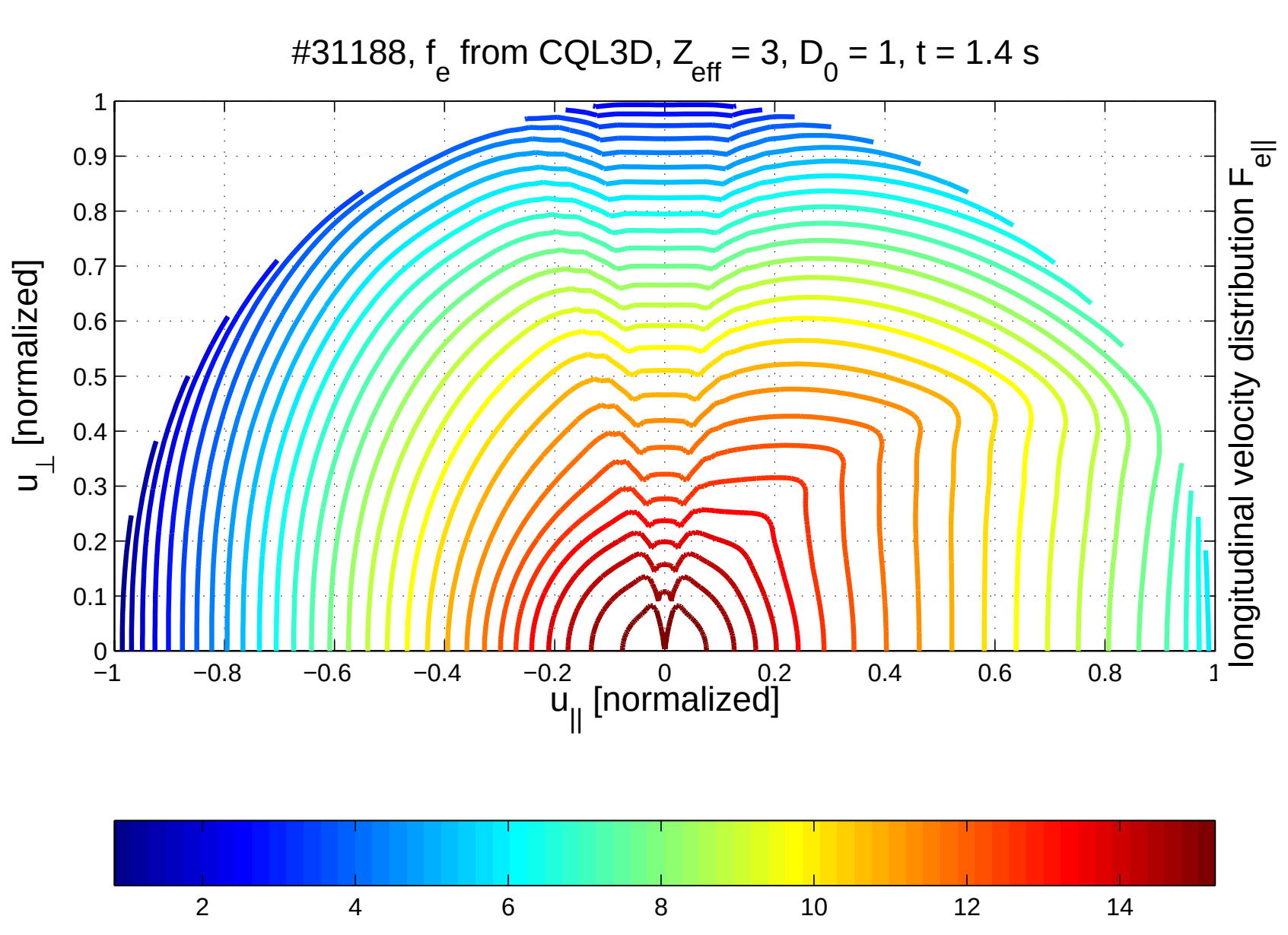
- Wave propagates at frequency $\omega_{\mathbf{k}}$, solution of the dispersion relation $\Re\epsilon(\mathbf{k},\omega) = 0$
- Instability growth rate given by $\gamma > 0$, where

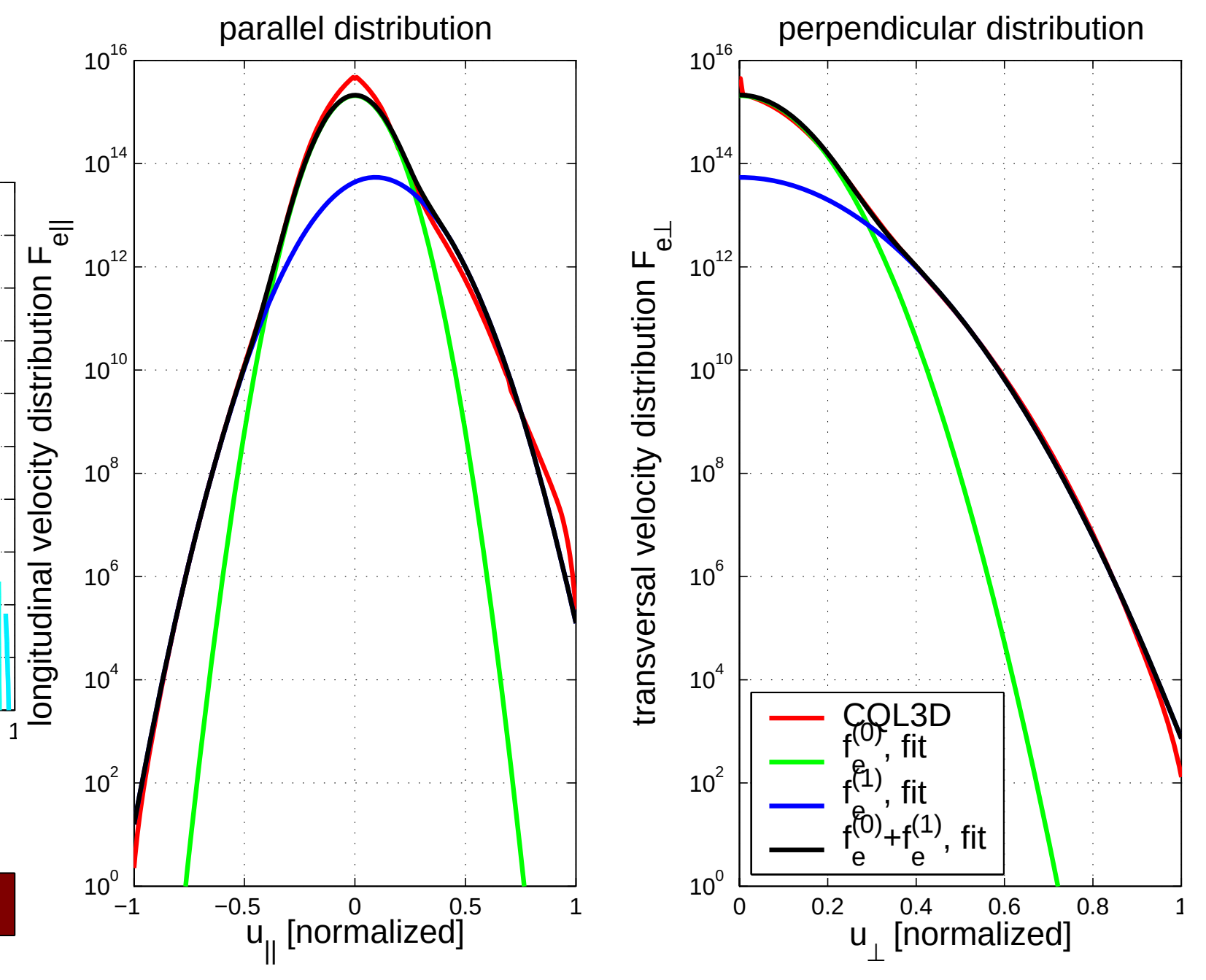
$$\gamma_{\mathbf{k}} = - \left. \frac{\Im\epsilon(\mathbf{k},\omega)}{\Re\frac{\delta\epsilon(\mathbf{k},\omega)}{\delta\omega}} \right|_{\omega=\omega_{\mathbf{k}}} \qquad (3)$$

- Ions are treated as unmagnetized. For $B \simeq 1.3$ T, $\omega_{pe} \approx |\Omega_{ce}|$, therefore only the Čerenkov interaction (n = 0) is considered for the electrons.

Simulation of f_e and Maxwellian approximation

- Simulation of the electron distribution function with quasilinear Fokker-Planck code CQL3D [4], example shown is discharge #31188, t=1.4 s, Z_{eff}=3, central suprathermal electron diffusivity D_0 = 1 m^2/s.
- Aim: solve the dispersion relation (equation 1) for maxwellian distributed populations
- 2D-fit of the electron distribution using two anisotropic maxwellians, one with parallel drift carrying the ECCD current.
- $T_e^{(0)}$ = 7 keV (consistent with Thomson scattering), $Te_\|^{(1)} \simeq Te_\perp^{(1)}$ = 15..20 keV, $n_e^{(0)}(\rho = 0) \sim 2{\cdot}10^{19} m^{-3}$ (SVD-inversion of 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 $J_{CD} = e n_e^{(1)} v_d^{(1)} \lesssim 10\ MA/m^2$.

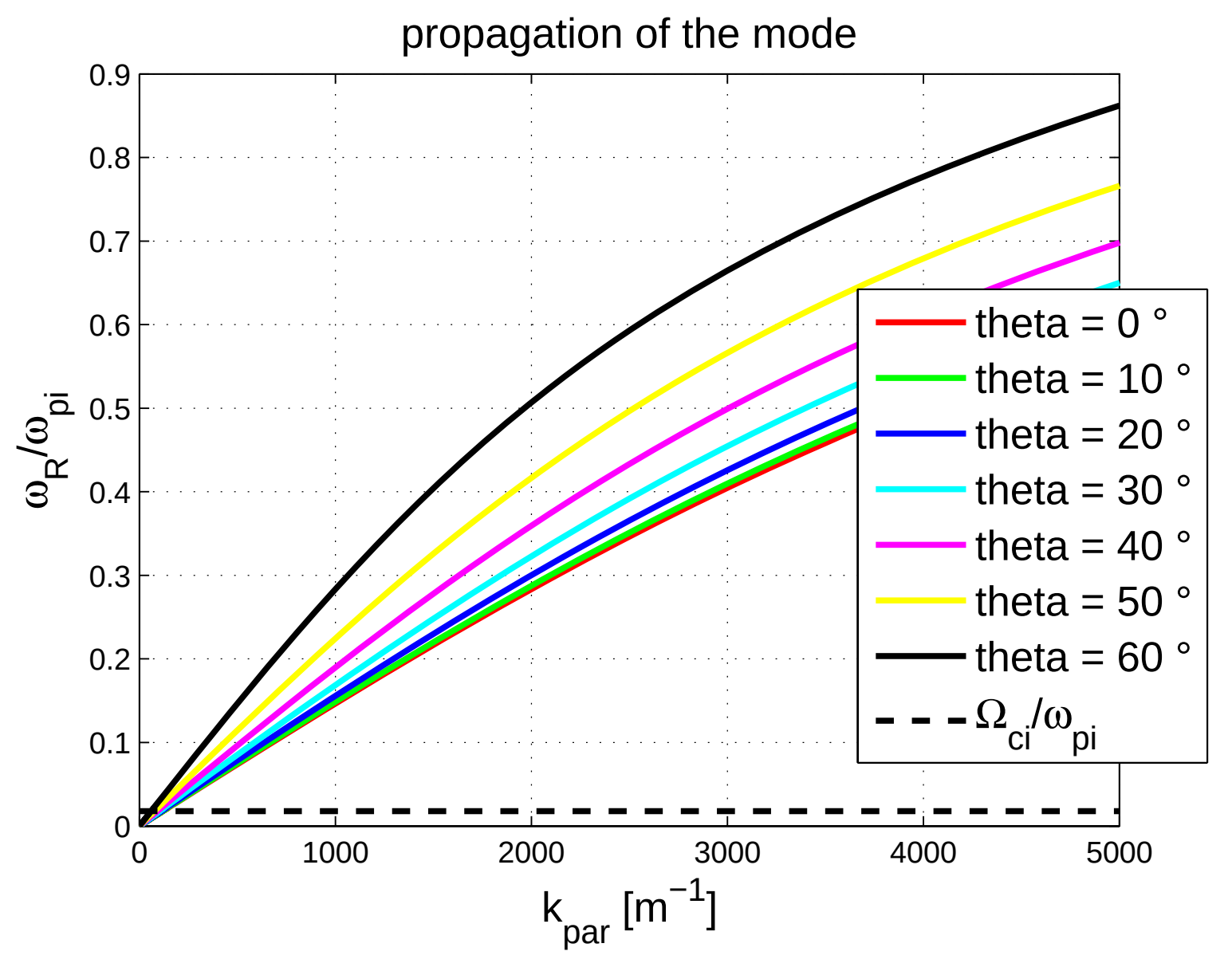




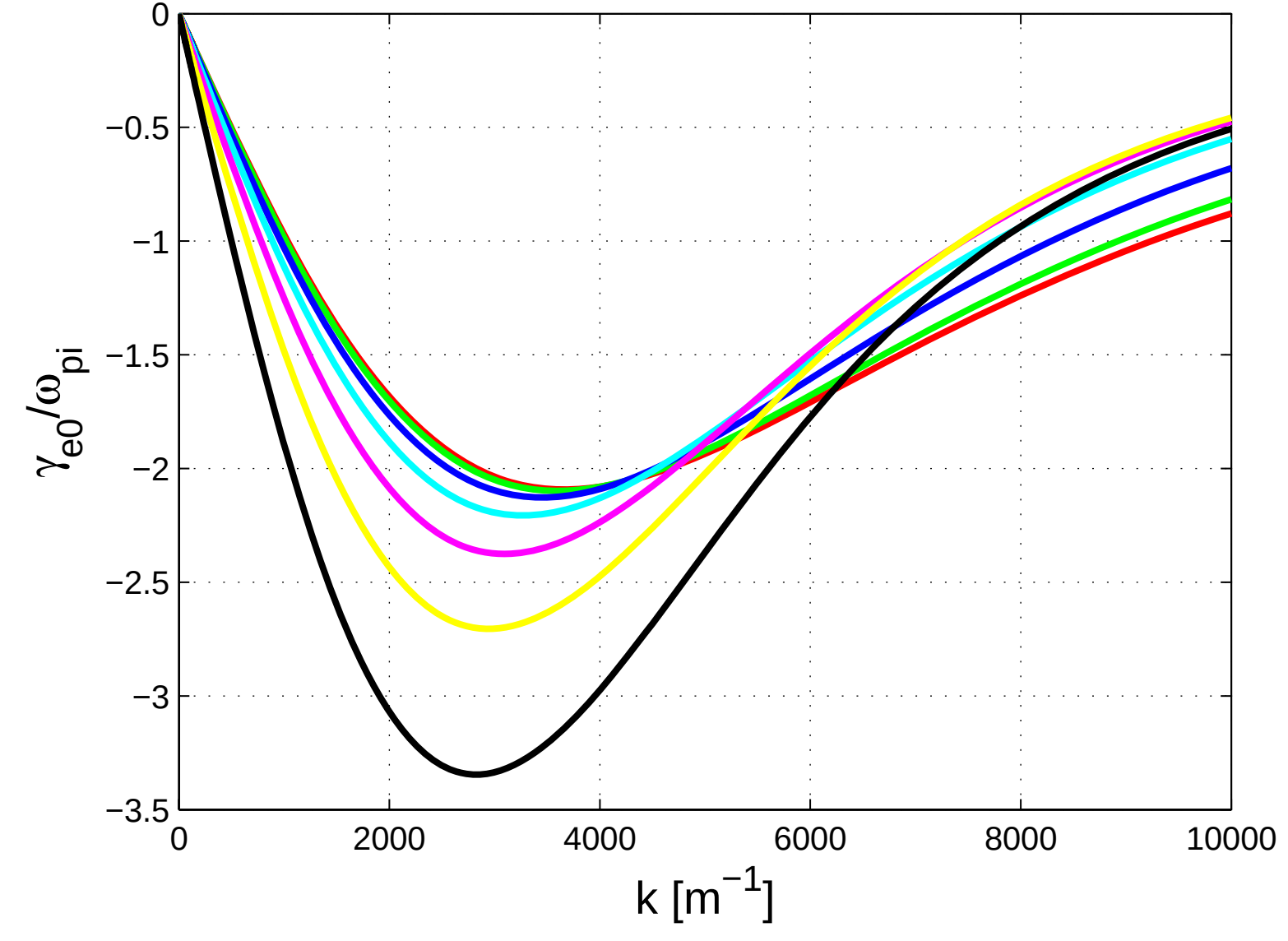
Compatible theoretical predictions (see poster P1.152)

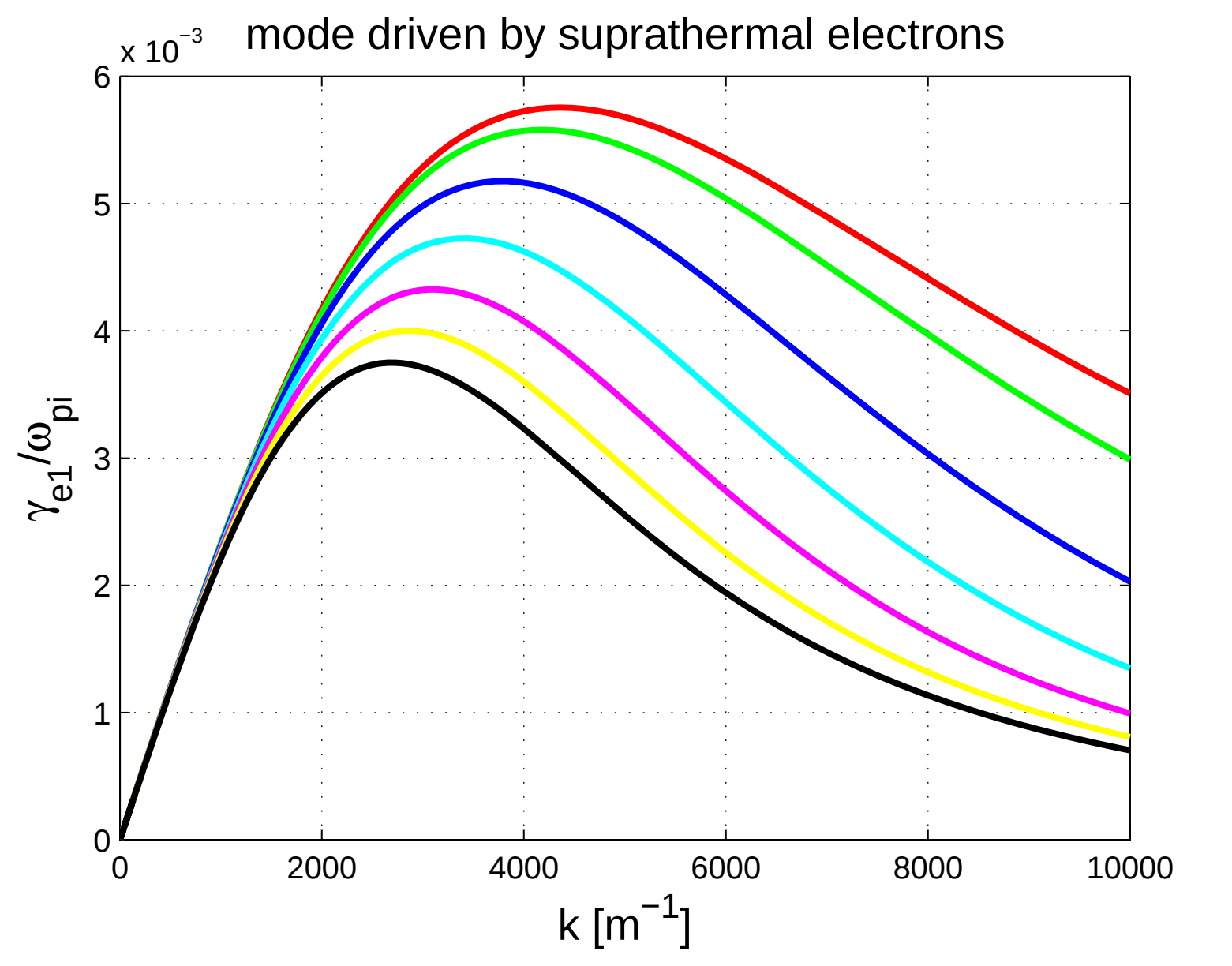
- increase of n_e: $n_e^{(1)}$ and $n_i^{(1)}$ decrease as ECCD efficiency (and $v_d^{(1)}$) decrease
- ϕ_{ECCD} scan: i.d.f. tail is most populated at maximum driven current.
- increase of I_p: toroidal electric field falls! Tail density and energy strongly decrease as well → less momentum transferred from electrons to ions → loss of anomalous resistivity.
- Quantitative estimations require to solve the quasilinear diffusion equation (work is in progress...)

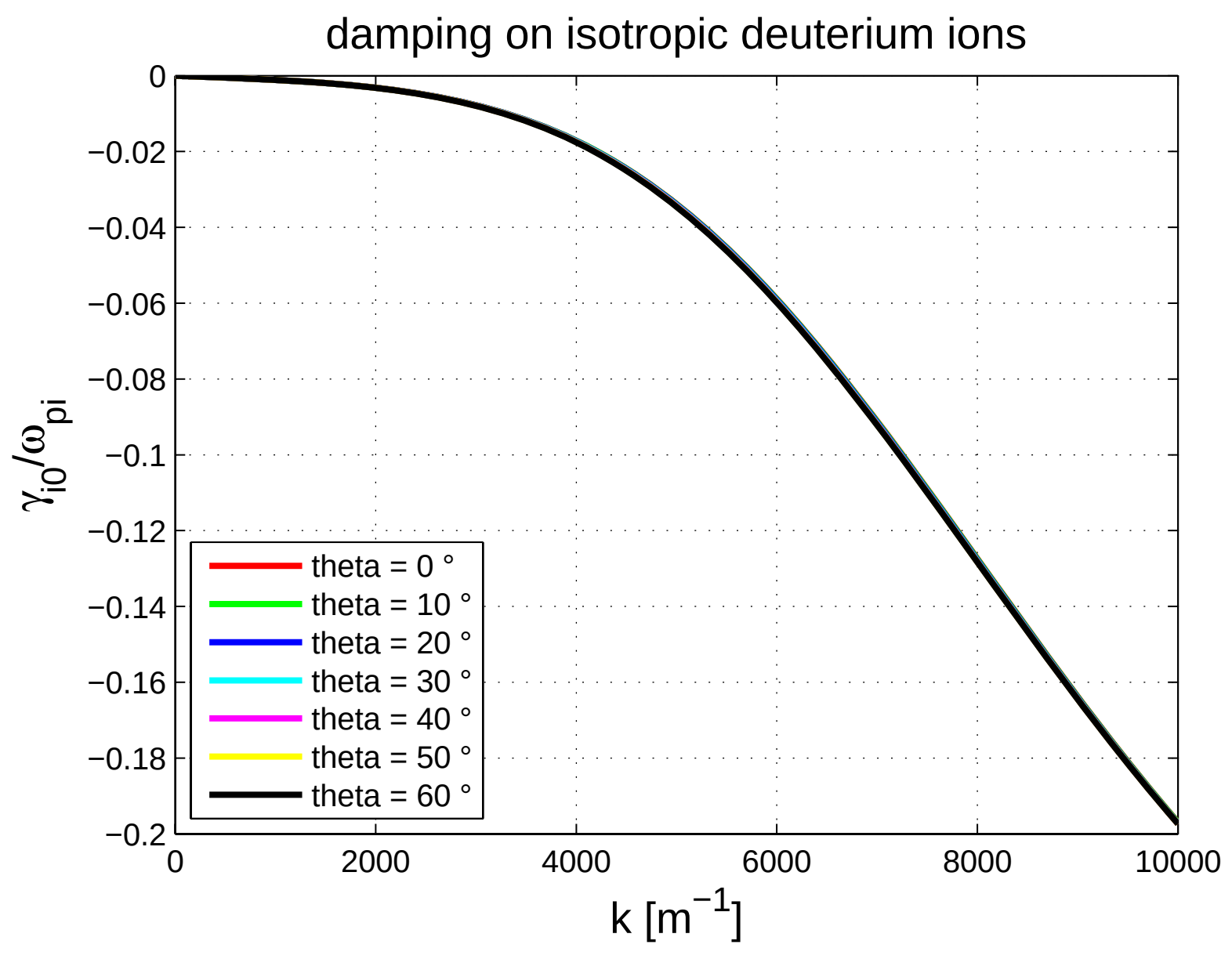
Conditions for the onset of the instability

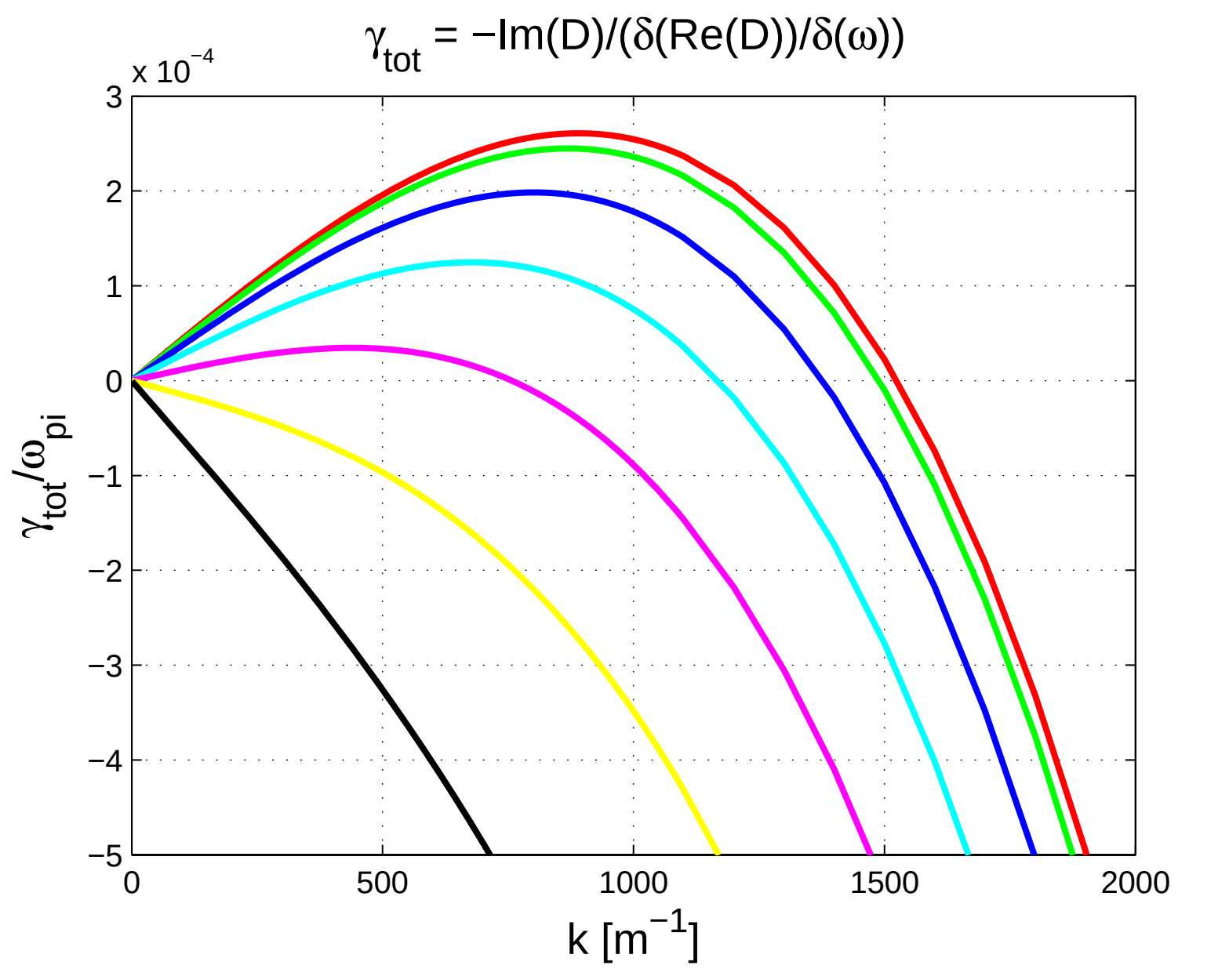


- the dispersion relation (equation 1) is solved numerically for $\Omega_{ci} \ll \omega_{\mathbf{k}} \ll |\, \Omega_{ce} \,|$
- the solution exists, the frequency is $\omega_{\mathbf{k}} \lesssim \omega_{pi}$.
- $v_{ph} = \frac{\omega_{\mathbf{k}}}{k_\|} < v_d^{(1)}$
- the plots show curves for different angles θ between wavenumber $\mathbf{k}$ and magnetic field $\mathbf{B}$.
- The excitation of the mode $\gamma_e^{(1)}$ can overcome the damping on the bulk electrons $\gamma_e^{(0)}$ and ions $\gamma_i^{(0)}$ below a threshold of θ.



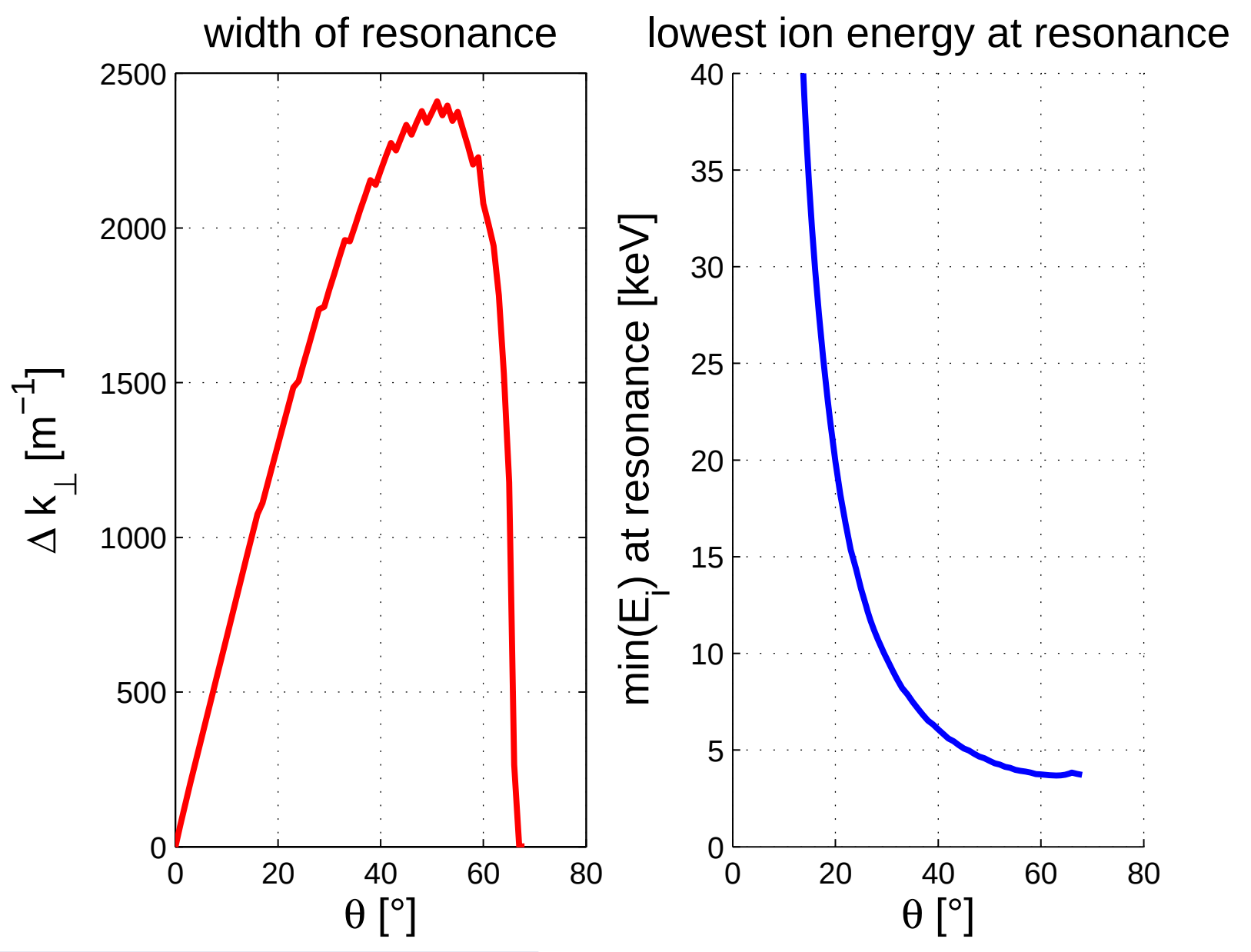






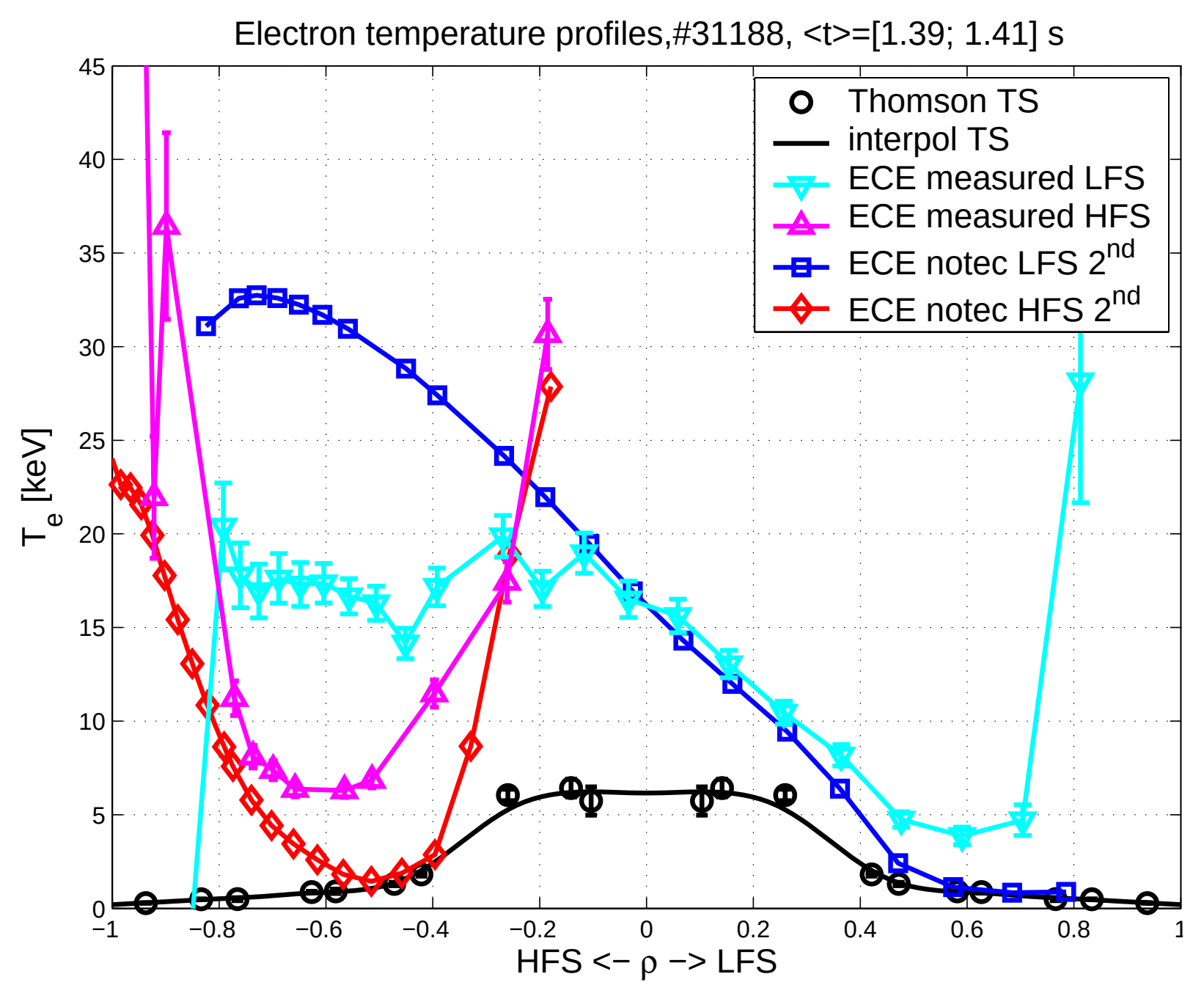
Conditions for simultaneous resonance of electrons and ions

- Resonance conditions for electrons and ions [3] derived from quantum mechanics $\mathbf{k} \cdot \mathbf{v_i} = \omega = k_\| v_{e1\|}$
- one-dimensional for the electrons, two-dimensional for the ions
- Figures show the width of the spread of perpendicular wave numbers at resonance and the minimum energy of the ions at resonance as a function of the angle between $\mathbf{k}$ and the magnetic field $\mathbf{B}$.



Alternative estimations of suprathermal electrons

- Electron cyclotron emission (ECE) measurements strongly influenced by the presence of suprathermal electrons.
- Measurements are modeled using the NOTEC ray-tracing code
- Simulation of discharge #31188 at t=1.2 s gives $n_e^{(1)}/n_e^{(0)}$ = 0.2, $T_{e\perp}^{(1)}$ = 35 keV, $\rho_e^{(1)} \simeq 0.4$.
- gives no estimation of $T_{e\|}^{(1)}$
- can only be used when the magnetic axis is located in front of the ECE antenna.



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[2] A. N. Karpushov et al., "Neutral particle analyzer diagnostics on the TCV Tokamak", Rev. Sci. Instrum. 77, 033504 (2006).
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