Ion-Acoustic Turbulence in ECCD-driven TCV plasmas

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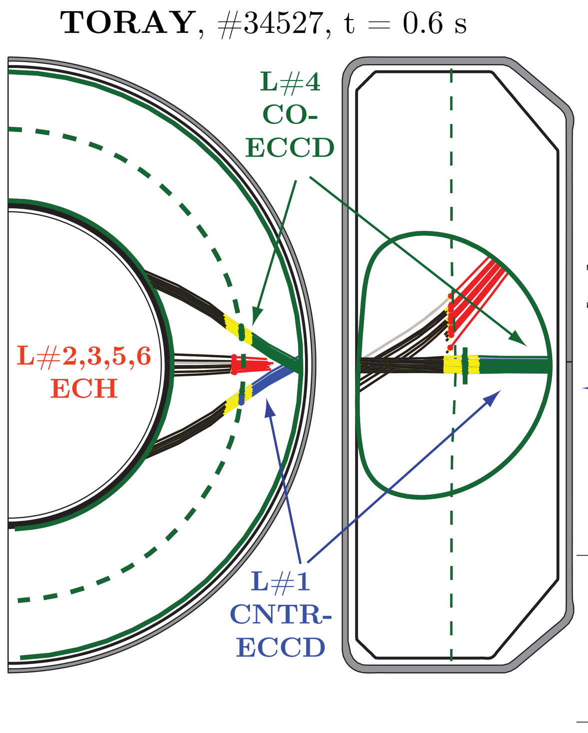
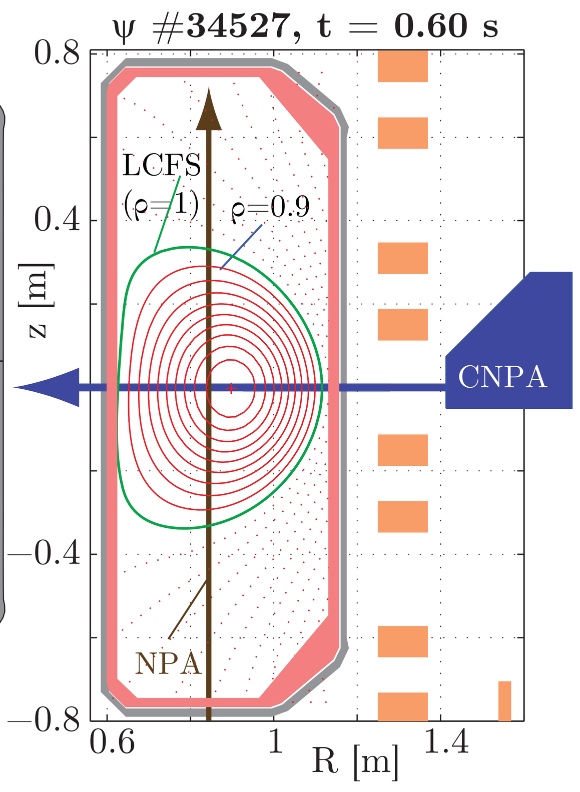
Observation of fast ions in ECCD discharges on TCV

Scenario & gyrotron setup

- 1..2 X2 ECCD on axis ($\rho \leq 0.1$)
- 1..4 X2 pure ECH off axis ($0.4 \leq \rho \leq 0.6$)
- high T_e^0 (∼eITB),
- low $I_p \lesssim 150$ kA,
- low $n_e(\rho = 0) \approx 2 \times 10^{-19}$ m^{-3}



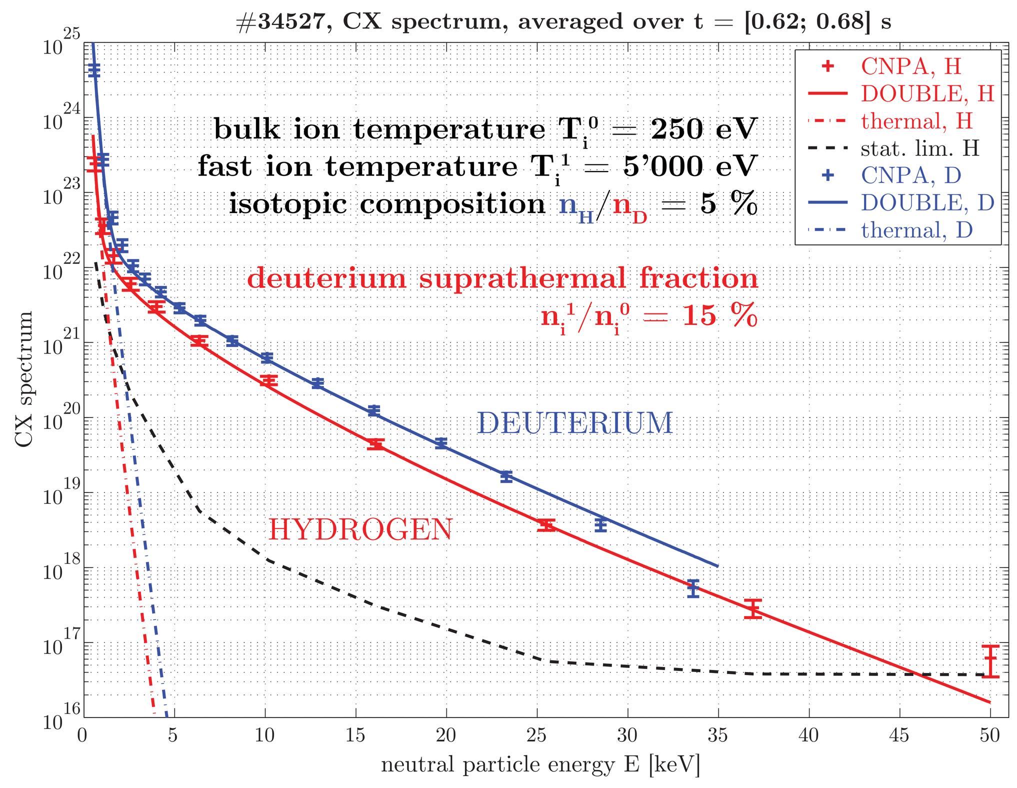


Ion Diagnostics

- vertical NPA, H+D, $E < 7$ keV
- CNPA, H, D, $E < 35/50$ keV
- CXRS, carbon, bulk ion profile

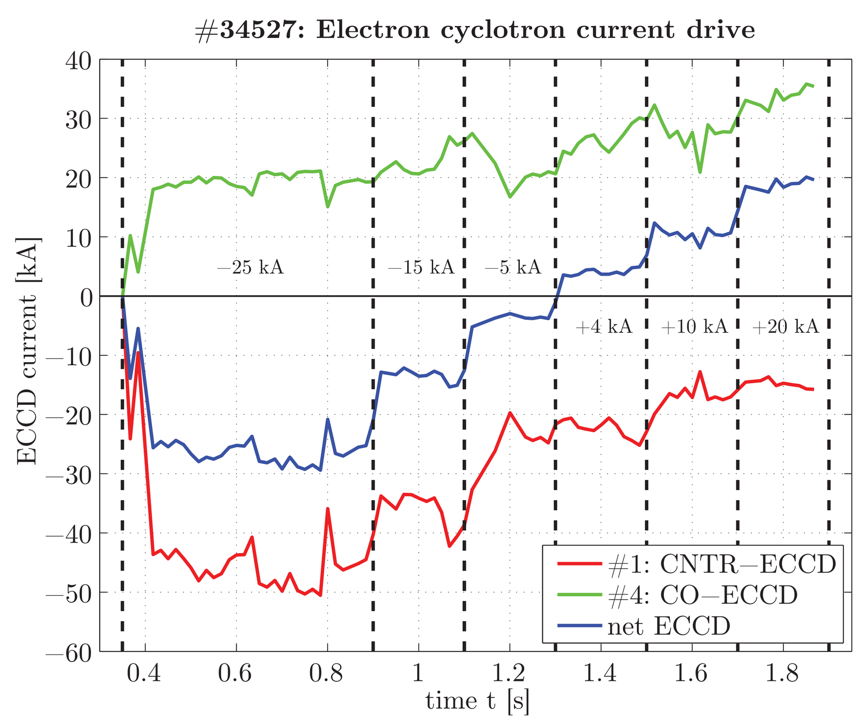
Bi-maxwellian $f_{i,\perp}$

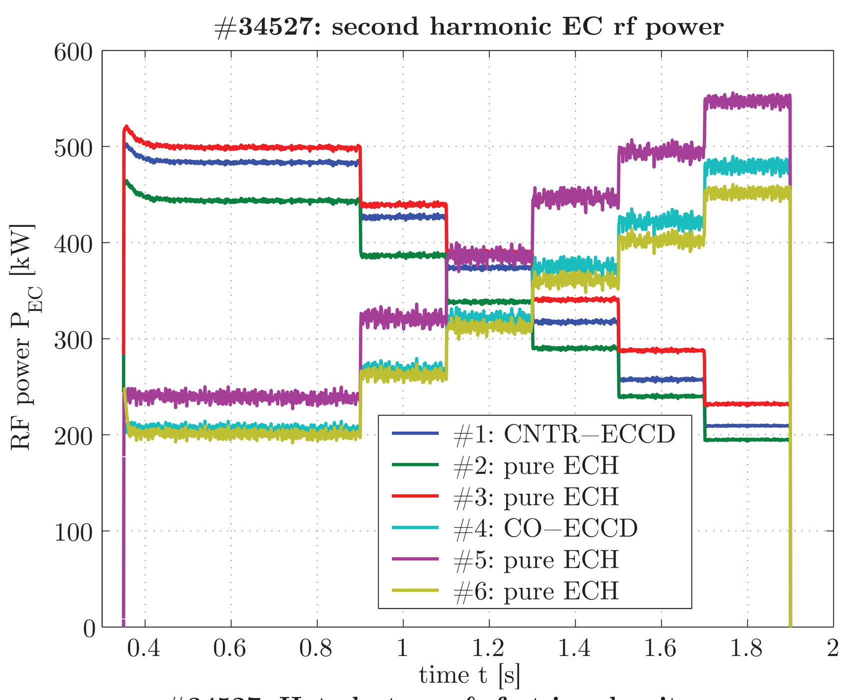
- CX neutral energy spectra bimaxwellian for Hydrogen and Deuterium
- radial (⊥B) view, inference of $T_{i\perp}$
- plasma at midplane, diagnostic chord through magnetic axis
- example #34527, fit at t = 0.6 s (maximum suprathermal population strength): $T_i^0(0) = 250$ eV, $T_i^1(0) = 5$ keV, $n_i^1/n_i^0 \sim 15$ %, $n_H/n_D \sim 5$ %
- Modeling using Monte Carlo code DOUBLE-TCV, with n_i^1/n_i^0 constant for $\rho \in [0; 0.7]$

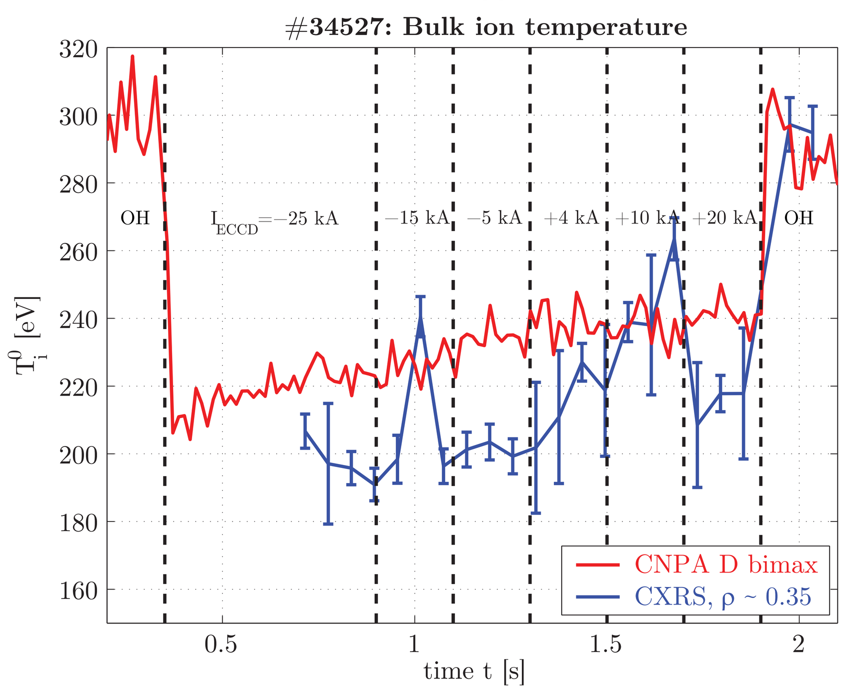


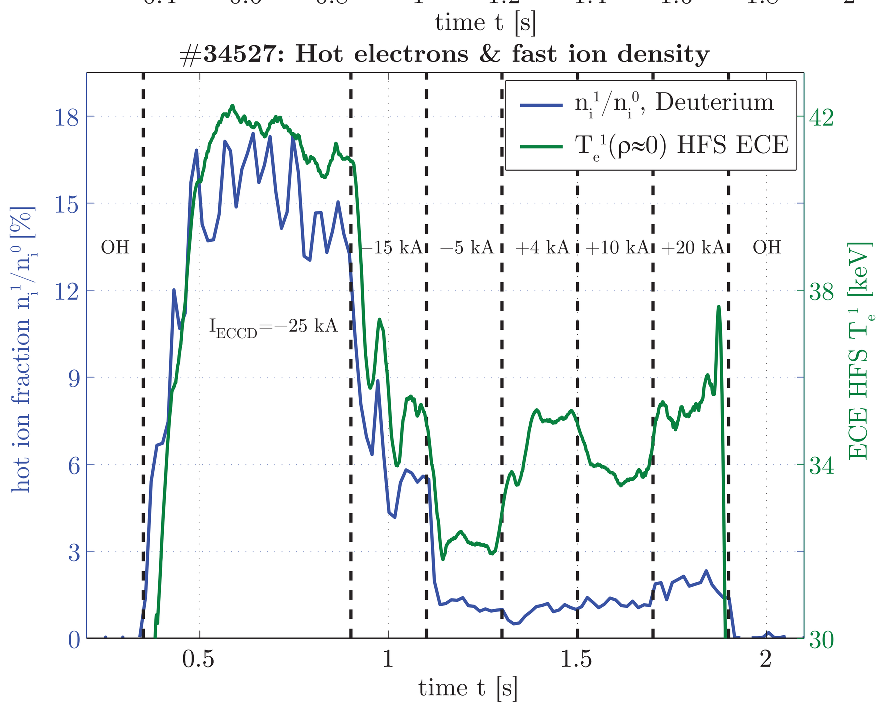
Steady-state fast ion population

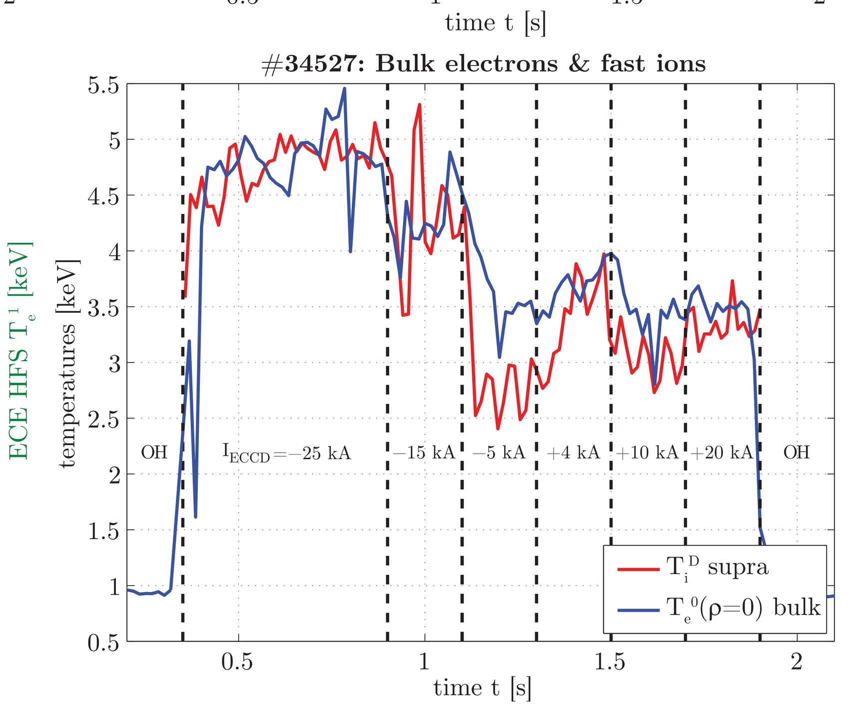
- Modulation of ECCD: staircase from CNTR to CO
- 4 gyrotrons doing ECH off-axis
- 2 gyrotrons ECCD on-axis, opposite direction
- maximum CNTR-ECCD starting $t = 0.35$ s
- net ECCD current calculated using TORAY
- for I_{ECCD}=cst, steady-state T_i^1, n_i^1
- weak effect even in pure ECH phase
- T_i^1 close to T_e^0
- n_i^1, W_i^1 correlate with T_e^1





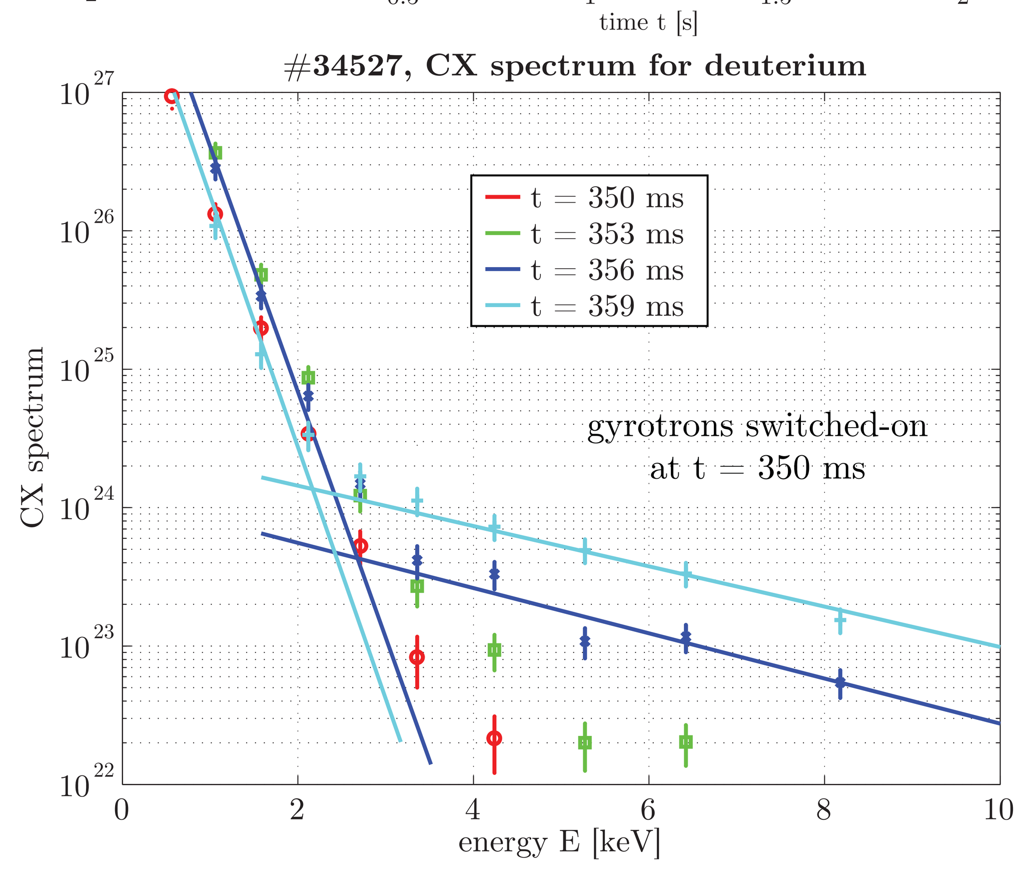






Temporal behavior and instability triggering

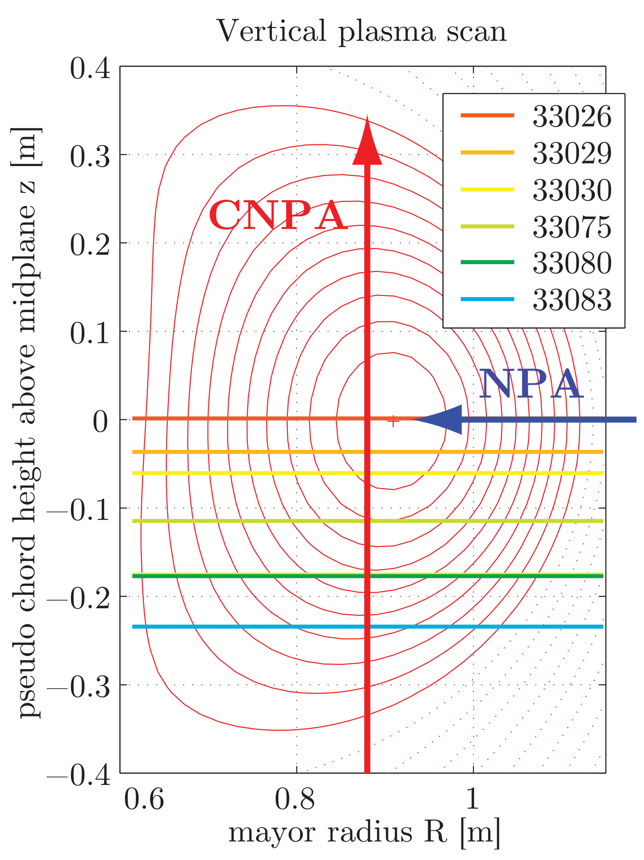
- suprathermal population appears immediately upon switch-on of ECCD
- population parameters settled after 6 ms only
- NPA time resolution (> 0.5 ms) insufficient to record tail dynamics
- Initial resonant energy of about the ion sound speed $c_S = \sqrt{\frac{T_e}{m_i}}$

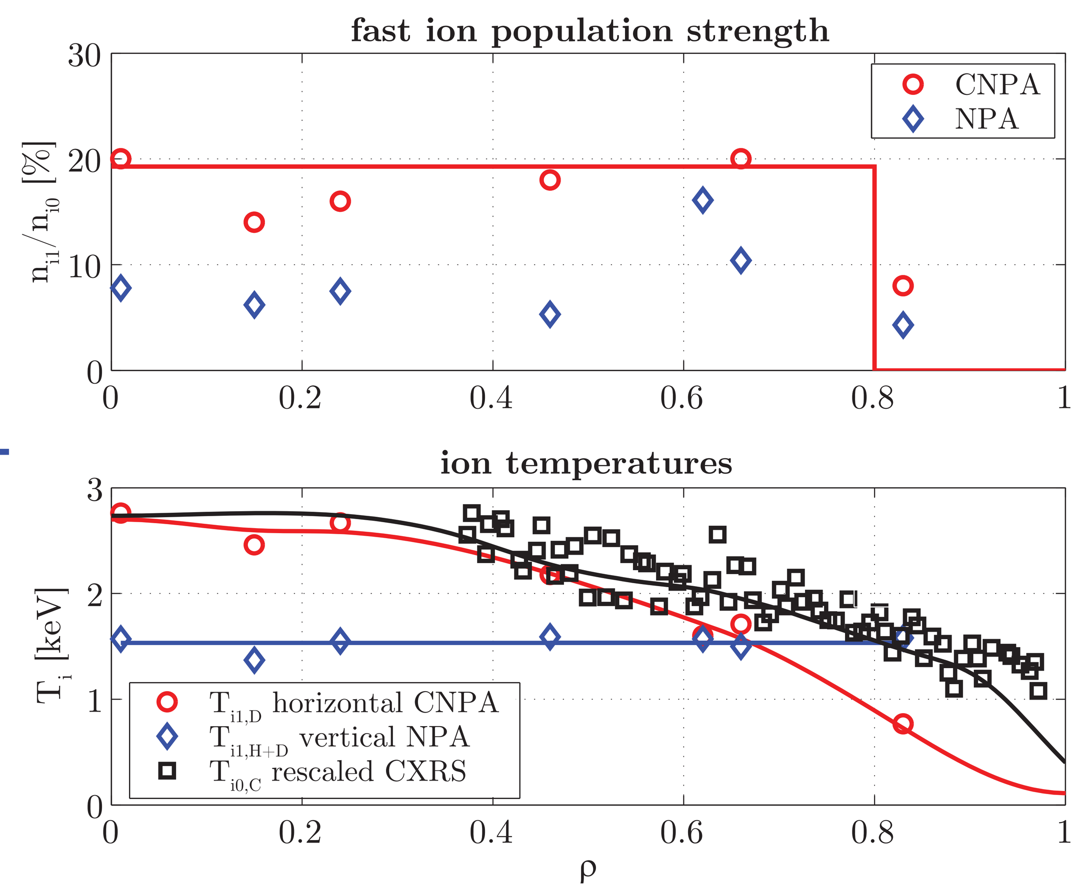


Suprathermal ion temperature profile

Vertical plasma displacement across CNPA view line

- Determination of suprathermal ion profile properties
- fixed CNPA at the midplane, plasma vertically displaced from shot-to-shot
- measurement of vertical NPA to ensure plasma reproducibility
- T_i^1 profile shape similar to T_i^0 (T_e^0 is peaked as we have a transport barrier, eITB)
- suprathermal fraction is constant, restricted to $\rho \leqslant 0.8$





Fast electrons: measurements and computer modeling

ECE diagnostics on TCV

- TCV has a HFS and a LFS ECE radiometer with perpendicular viewing antennae
- A movable gyrotron launcher is used for oblique views, both CO and CNTR direction

EC emission modeling using NOTEC-TCV code

- 3D ECE raytracing using the real antenna pattern based on geometrical optics (cold plasma approximation)
- developed for JET 20 years ago, adapted for TCV to interface with our database and setup
- Wall description (radiation reflection), refraction, relativistic, non-thermal electron distributions
- experimental profiles from MDS, suprathermal populations recovered by reverse-engineering
- currently only a circular plasma is implemented (is not a problem if plasma in front of antenna)
- simultaneous modeling of TCV LFS and HFS antennae reception to recover full electron properties

- Population 0: bulk electrons

  $n_{e0} = 2.4 \times 10^{-19}$ m^{-3}, $T_{e0} = 3$ keV, peaked profile, $I_p = 140$ kA

- Population 1: center ECCD

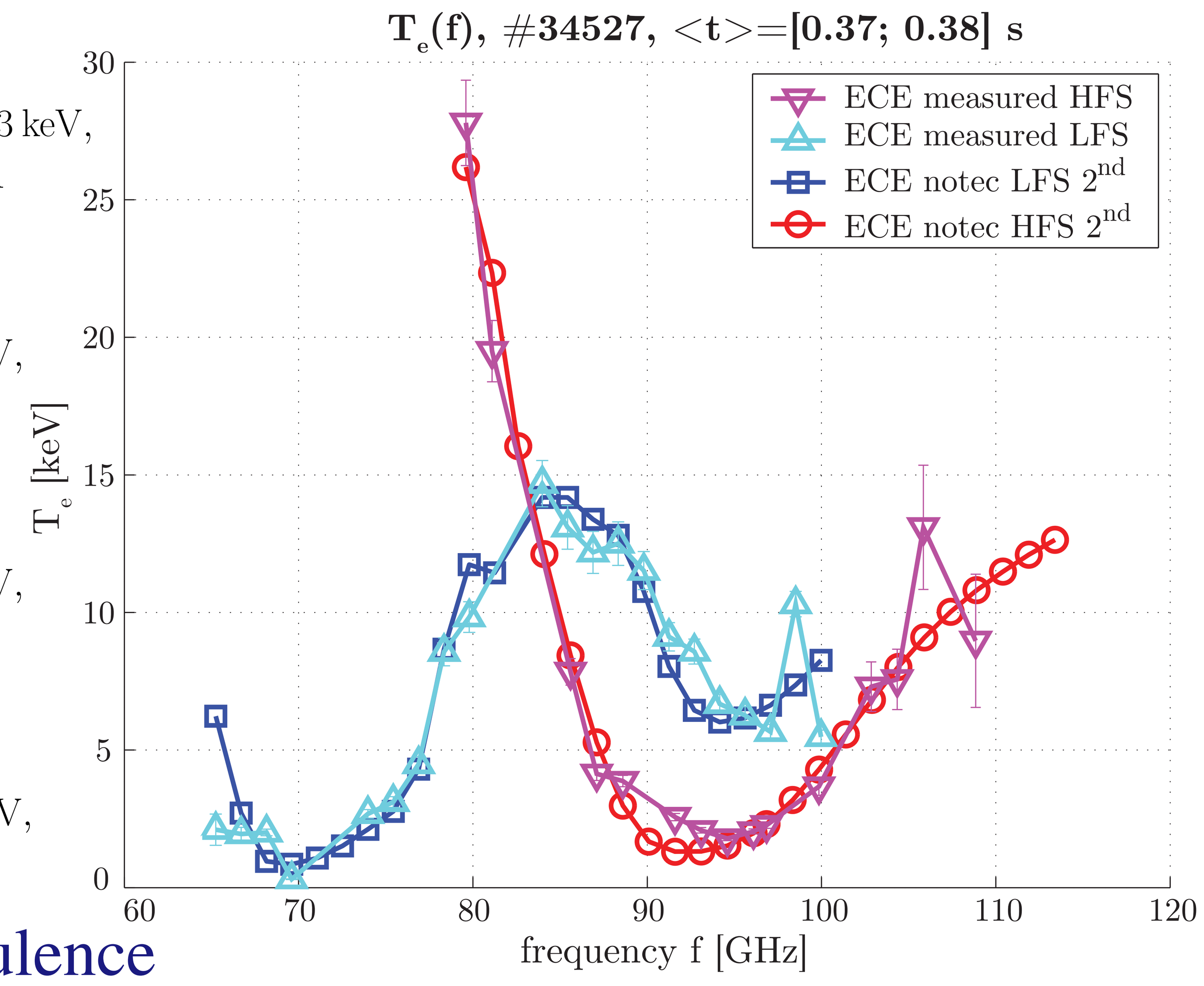
  $n_{e1}/n_{e0} = 0.8$, $E_{\perp 1} = 15$ keV, $\rho_1 \in [0;\ 0.05]$, $\beta_1 = 0.15$

- Population 2: extended core

  $n_{e2}/n_{e0} = 0.5$, $E_{\perp 2} = 15$ keV, $\rho_2 \in [0.1;\ 0.2]$, $\beta_2 = 0.1$

- Population 3: off-axis ECH

  $n_{e3}/n_{e0} = 0.02$, $E_{\perp 3} = 35$ keV, $\rho_3 \in [0.2;\ 0.45]$, $\beta_3 = 0$



Ion-Acoustic Turbulence

Observation	Requirements	ECCD current-driven Ion Acoustic Instability
require fast electrons	v_{de} relativistic	unstable if $v_d > c_s$
T_e^0 needs to be hot	T_e^0/T_i^0 must be high (eITB)	growing if $T_e \gg T_i$
appear very fast (≪ ms)	wave-particle interaction	growth within $10..100\,\omega_{pi} \rightarrow \mu s$
⊥ energization	efficient energy transfer to ions ⊥B	scattering of sound by ions, resonance $kv_{\parallel,e} = \omega_{\mathbf{k}} = \mathbf{k} \cdot \mathbf{v}_i$ 1D for e, 3D for i
T_i^1 of order T_e^0	T_i^1 cannot exceed T_e^0	stabilized if $T_i = T_e$
steady-state f_i tail	saturation of process	fast ions may quench the instability
resonant and non-resonant	resonant $v_{\mathrm{ion}} = c_s$	$v_{ph} \sim c_s$, D_R and D_{NR}
run–away suppression	momentum transfer $e \rightarrow i$	anomalous resistivity

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Linear theory of IAT

Dielectric function in magnetized plasma

- Dispersion relation $\epsilon(\mathbf{k},\omega) = 1 - \sum_\alpha \frac{\omega_{p\alpha}^2}{k^2} \sum_{n=-\infty}^{+\infty} \int \mathrm{d}^3v \left(\frac{n\Omega_\alpha}{v\perp}\frac{\partial f_\alpha}{\partial v\perp} + k_\parallel \frac{\partial f_\alpha}{\partial v\|} \right) \frac{J_n^2(\zeta)}{n\Omega_\alpha + k_\parallel v_\parallel - \omega}$
  where $J_n^2(\zeta)$ is the Bessel function of order n and $\zeta = \frac{k_\perp v_\perp}{\Omega_\alpha}$
- approximations: **ions**: rather cold $T_i \ll T_e$, non-magnetized
  electrons: temperature anisotropy may play a role. $\omega_{pe} \approx \Omega_{ce}$

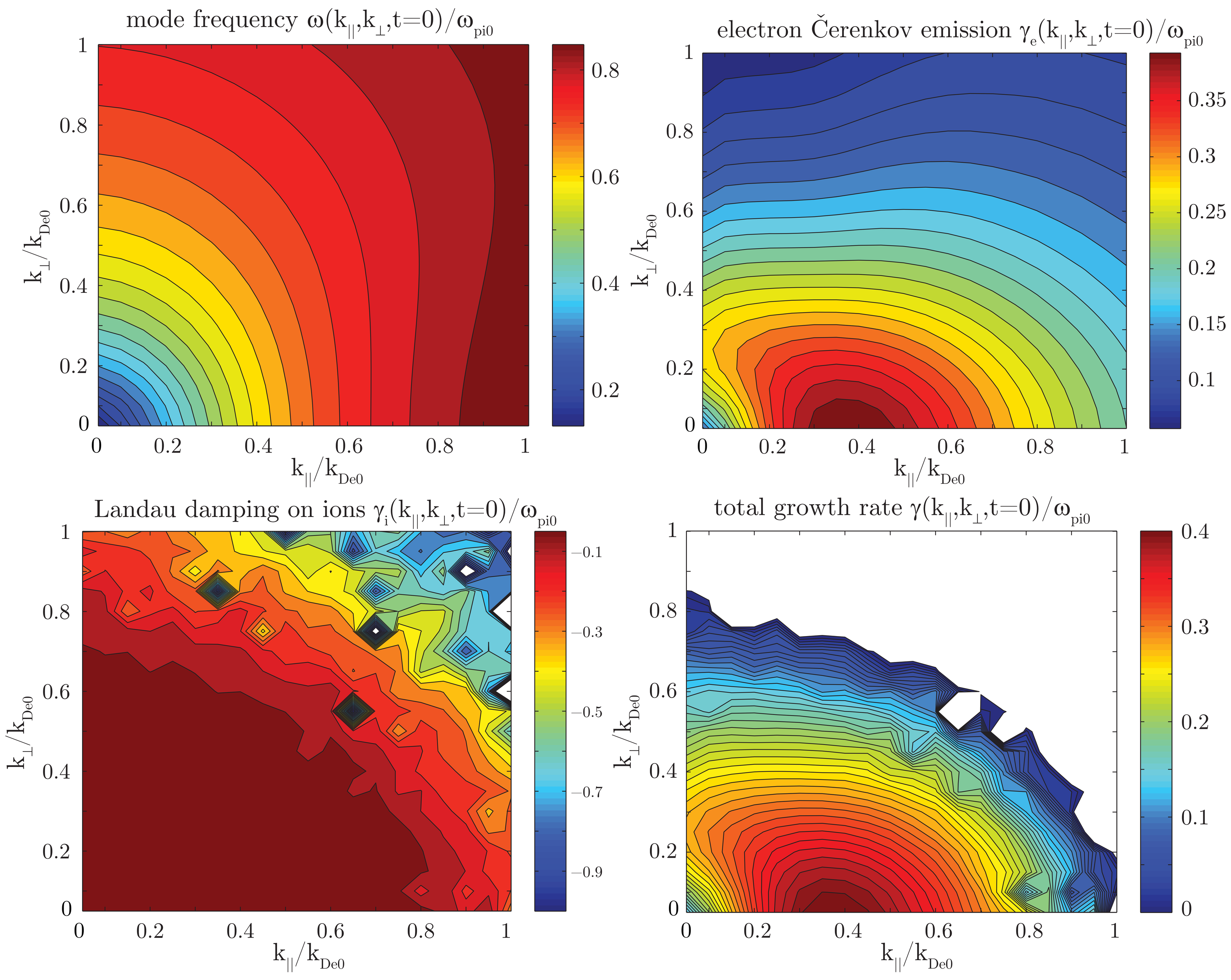
$$\Re\left\{\epsilon(\mathbf{k},\omega)\right\} = 1 - \frac{\omega_{pi}^2}{\omega_{\mathbf{k}}^2} + \frac{k_{D\|}^2}{k^2}\left(1 - \frac{2\,v_d^2}{v_{\mathrm{the}\|}^2 \exp(-\frac{1}{2}\zeta^2) I_0(\frac{1}{2}\zeta^2)}\right) + \frac{k_{D\perp}}{k^2}(1-\tau_e)\left(1 - \exp(-\frac{1}{2}\zeta^2)\right) I_0(\frac{1}{2}\zeta^2) = 0$$

with $I_0(x)$ the modified 0-order first kind Bessel function, $\tau_\alpha = \frac{T_{\alpha\perp}}{T_{\alpha\|}}$.

- Oscillation frequency $\omega_{\mathbf{k}}$ numerically determined from $\Re\left\{\epsilon(\mathbf{k},\omega)\right\} = 0$
- Instability growth rate determined from $\gamma_{\mathbf{k}} = -\left.\frac{\Im\epsilon(\mathbf{k},\omega)}{\Re\frac{\partial\epsilon(\mathbf{k},\omega)}{\partial\omega}}\right|_{\omega=\omega_{\mathbf{k}}} = \gamma_e + \gamma_i$
- Landau damping on the ions $\gamma_i = \frac{\omega_{\mathbf{k}}{}^3}{2\omega_{pi}^2}\frac{4\pi Z^2 e^2}{m_i k^2}\int \mathrm{d}^3v \left(\frac{k_\perp \frac{\omega_{\mathbf{k}} - k_\| v\|}{k_\perp v_\perp}\frac{\partial f_i}{\partial v_\perp} + k_\| \frac{\partial f_i}{\partial v_\|}}{\sqrt{(k_\perp v_\perp)^2 - (\omega_{\mathbf{k}} - k_\| v_\|)^2}} \right)$
- Mainly Čerenkov emission (n = 0) by the drifting electrons

$$\gamma_e = \frac{\omega_{\mathbf{k}}{}^3}{2\omega_{pi}^2}\frac{4\pi^2 Z^2 e^2}{m_e k^2}\int \mathrm{d}^3v \sum_{n=-\infty}^{+\infty} J_n^2\left(\frac{k_\perp v_\perp}{\Omega_{ce}}\right)\delta(\omega_{\mathbf{k}} - k_\| v_\| - n\Omega_{ce})\left(k_\perp \frac{n\Omega_{ce}}{k_\perp v_\perp}\frac{\partial f_e}{\partial v_\perp} + k_\| \frac{\partial f_e}{\partial v_\|}\right)$$

Excitation in TCV ECCD discharges



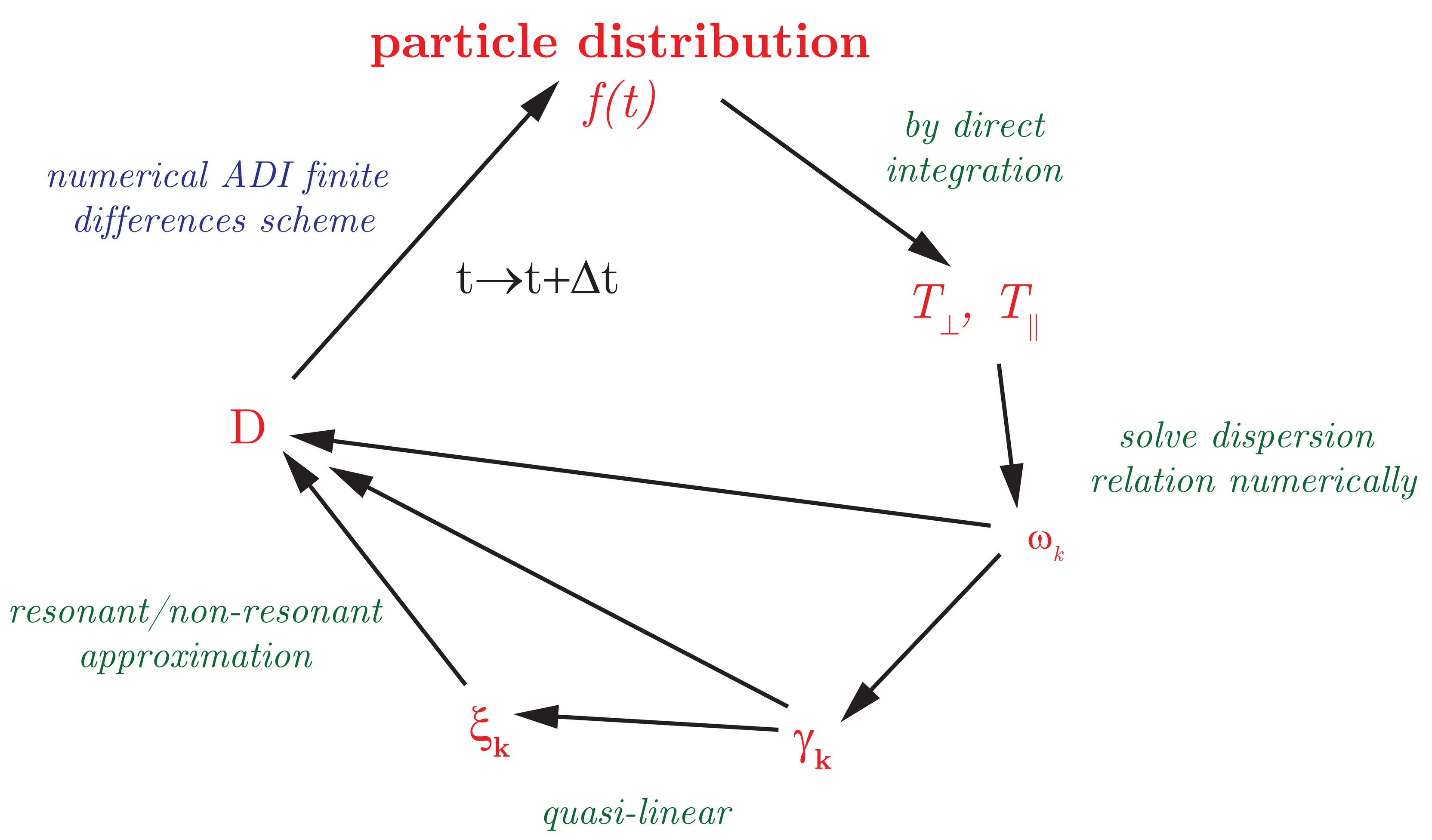
Quasi-linear diffusion of $f_i(\mathbf{v},t)$ in IAT

- If $\gamma_{\mathbf{k}} \ll \omega_{\mathbf{k}}$, quasi-linear theory is applicable. Quasi-linear diffusion equation:

$$\begin{cases} \frac{\partial f_\alpha(\mathbf{v})}{\partial t} = \frac{\partial}{\partial \mathbf{v}} \cdot \mathrm{D}_\alpha \cdot \frac{\partial f_\alpha(\mathbf{v})}{\partial \mathbf{v}}, \\ \frac{\partial \mathcal{E}_{\mathbf{k}}}{\partial t} = 2\,\gamma_{\mathbf{k}}\mathcal{E}_{\mathbf{k}} \end{cases}$$

- Here we want to describe $f_i(\mathbf{v},t)$ and $f_e(\mathbf{v},t)$ in a uniform plasma in a constant magnetic field and a constant current along the magnetic field.
- Solve quasi-linear diffusion equation for electrons and ions simultaneously using a numerical algorithm
- Quasi-linear diffusion coefficients are taken from [5] (D_e), [6] $\left(\text{resonant } \mathrm{D}_i^{\mathrm{R}} \sim \sum_{\mathbf{k}} \mathcal{E}_{\mathbf{k}}\delta\left(\omega_{\mathbf{k}} - kv\right)\right)$ and [7] $\left(\text{non}-\text{resonant } \mathrm{D}_i^{\mathrm{R}} \sim \sum_{\mathbf{k}} \mathcal{E}_{\mathbf{k}} \frac{\gamma_{\mathbf{k}}}{(\omega_{\mathbf{k}} - kv)^2}\right)$.

Outline of the numerical algorithm



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Alternating direct implicit finite difference scheme

- projection on grid: $f_{i,j}^n = f(i\Delta v_\perp, j\Delta v_\|, n\Delta t)$
- first half time step, implicit difference in $\|$, explicit in $\perp$ (reversed for $n+1$):

$$(f^{n+1/2} - f^n)/(\Delta t/2) = D_{\|,\|}^n \delta_\|^2 f^{n+1/2} + \left[\frac{\partial D_{\|,\|}}{\partial v_\|} + \frac{D_{\perp,\|}}{v_\perp} + \frac{\partial D_{\perp,\|}}{\partial v_\perp}\right] f^{n+1/2}$$
$$+2D_{\perp,\|}^n \delta_{\perp,\|}^2 \frac{1}{2}\left(f^{n+1/2} + f^n\right) + \left[\frac{\partial D_{\|,\perp}}{\partial v_\|} + \frac{D_{\perp,\perp}}{v_\perp} + \frac{\partial D_{\perp,\perp}}{\partial v_\perp}\right] f^n + D_{\perp,\perp}^n \delta_{\perp,\perp}^2 f^n$$

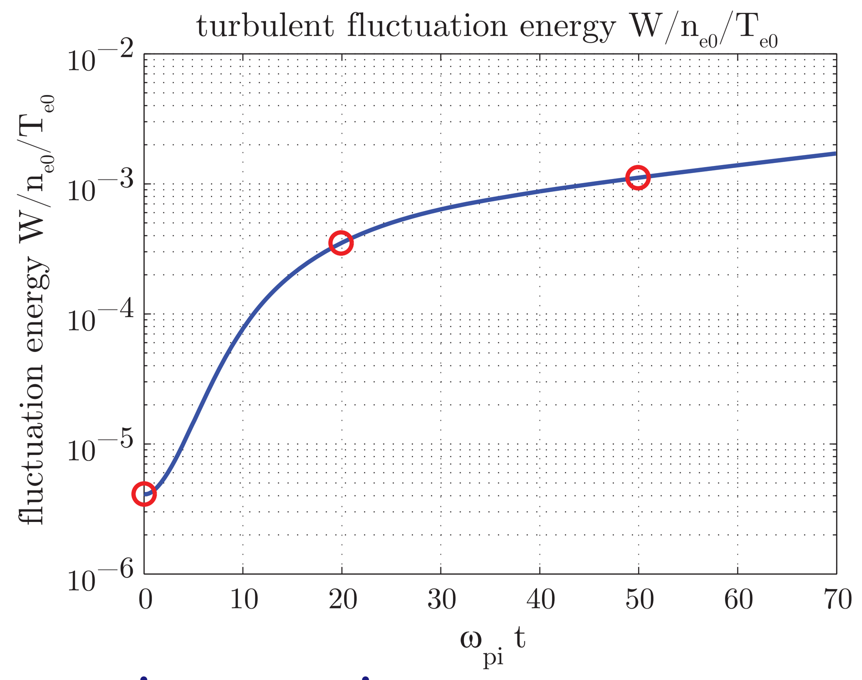
- initial condition: Maxwellians, f_i isotropic, f_e drifting with v_d, small initial fluctuation energy $\xi_{\mathbf{k}} \ll n_{e0}T_{e0}$
- boundary conditions: $f = 0$ for $v \to \infty$ and

$$\frac{\partial f_e(v_\perp = 0)}{\partial v_\perp} = \frac{\partial f_i(v_\perp = 0)}{\partial v_\perp} = \frac{\partial f_i(v_\| = 0)}{\partial v_\|} = 0$$

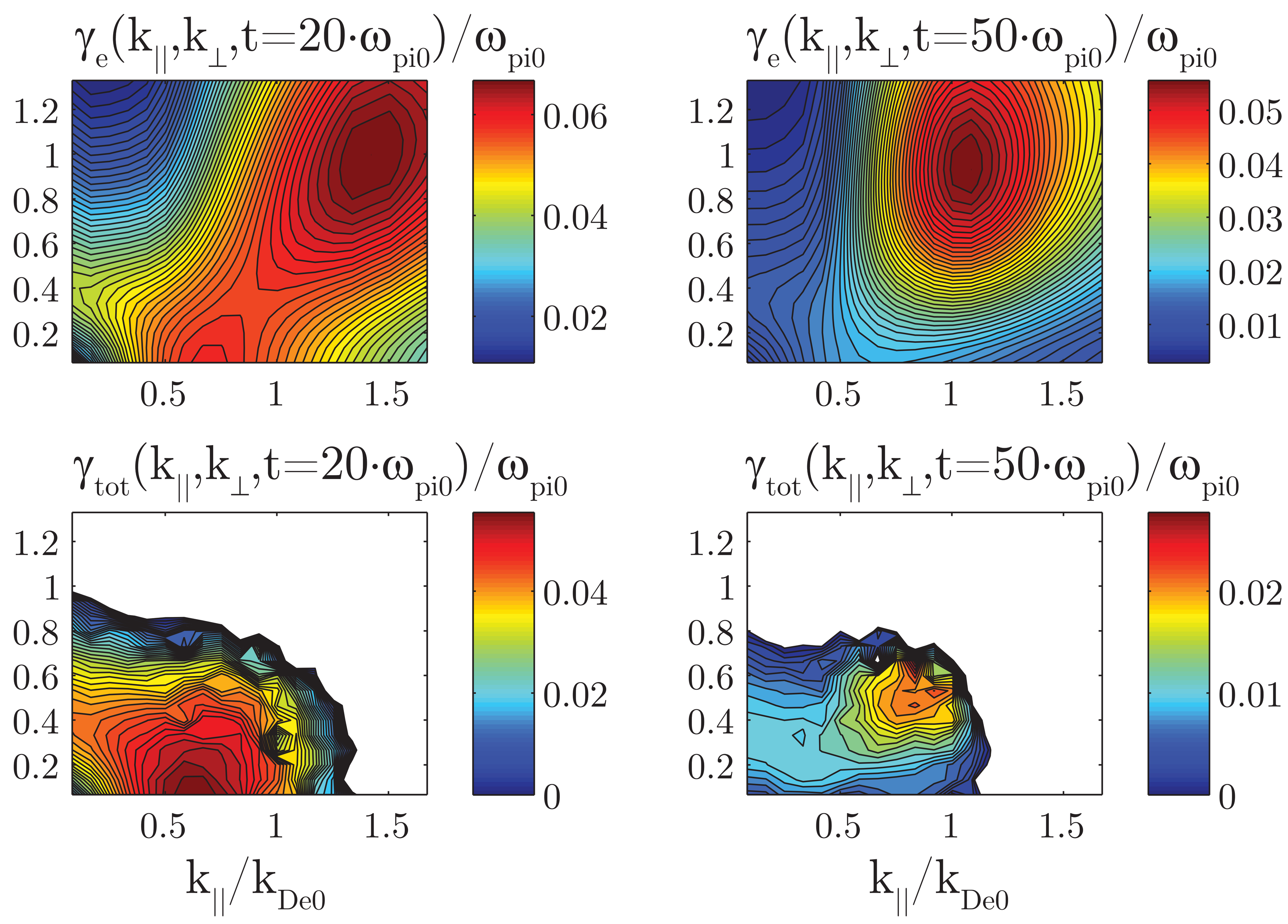
- Resolution using recurrence formulas sweeping out and back along dimensions.
- Currently the current is kept constant through an external electric field

$$\frac{\partial}{\partial t}\mathbf{j} = e\,n_0\frac{\partial}{\partial t}\int f_e(\mathbf{v},t)\,v_\|\mathrm{d}^3v = 0$$
$$\text{from } \frac{\partial f_\alpha(\mathbf{v})}{\partial t} = \frac{\partial}{\partial \mathbf{v}} \cdot \mathrm{D}_\alpha \cdot \frac{\partial f_\alpha(\mathbf{v})}{\partial \mathbf{v}}$$
$$\to E_0 = -\frac{m_e}{n_0 e}\int \mathrm{d}^3v v_\| \frac{\partial}{\partial \mathbf{v}} \cdot \mathrm{D}_\alpha \cdot \frac{\partial f_\alpha(\mathbf{v})}{\partial \mathbf{v}}$$

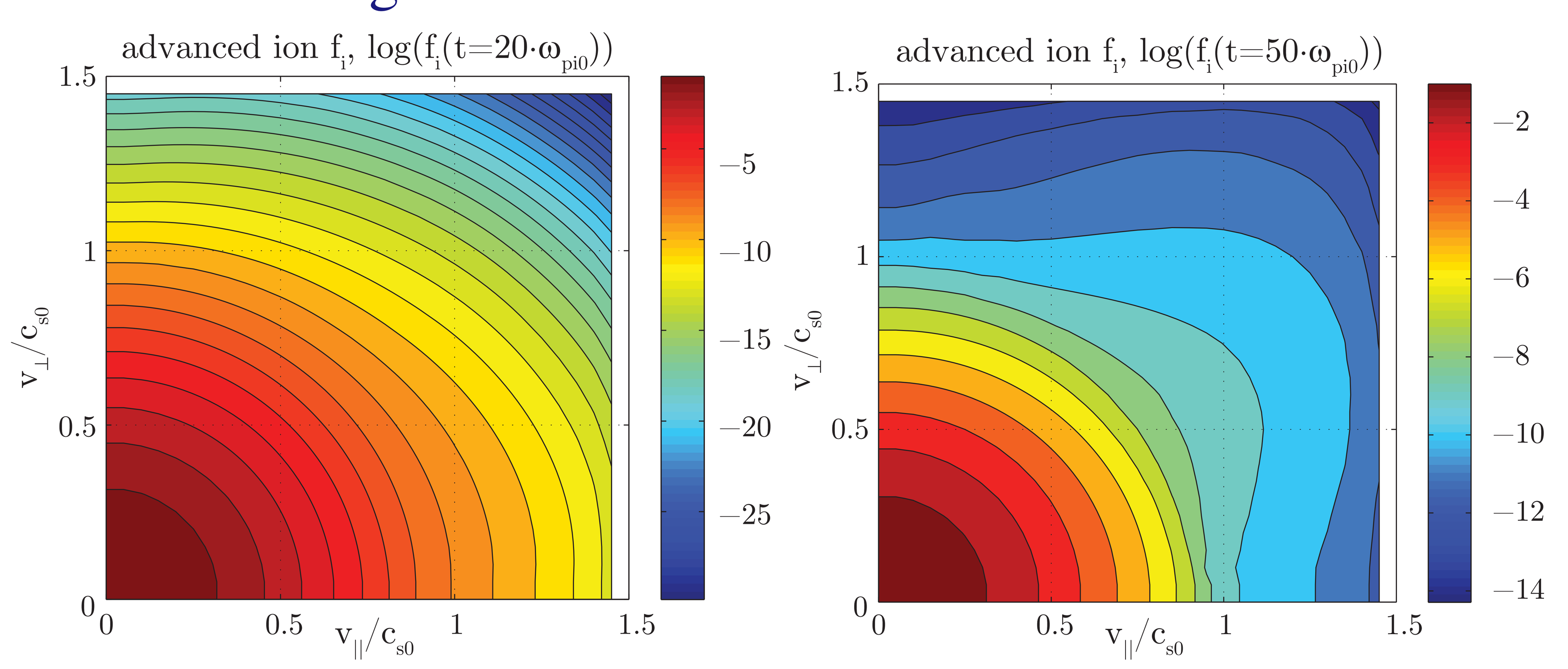
- integration of additional electron diffusion tensors describing the EC current drive is desirable (work in progress)

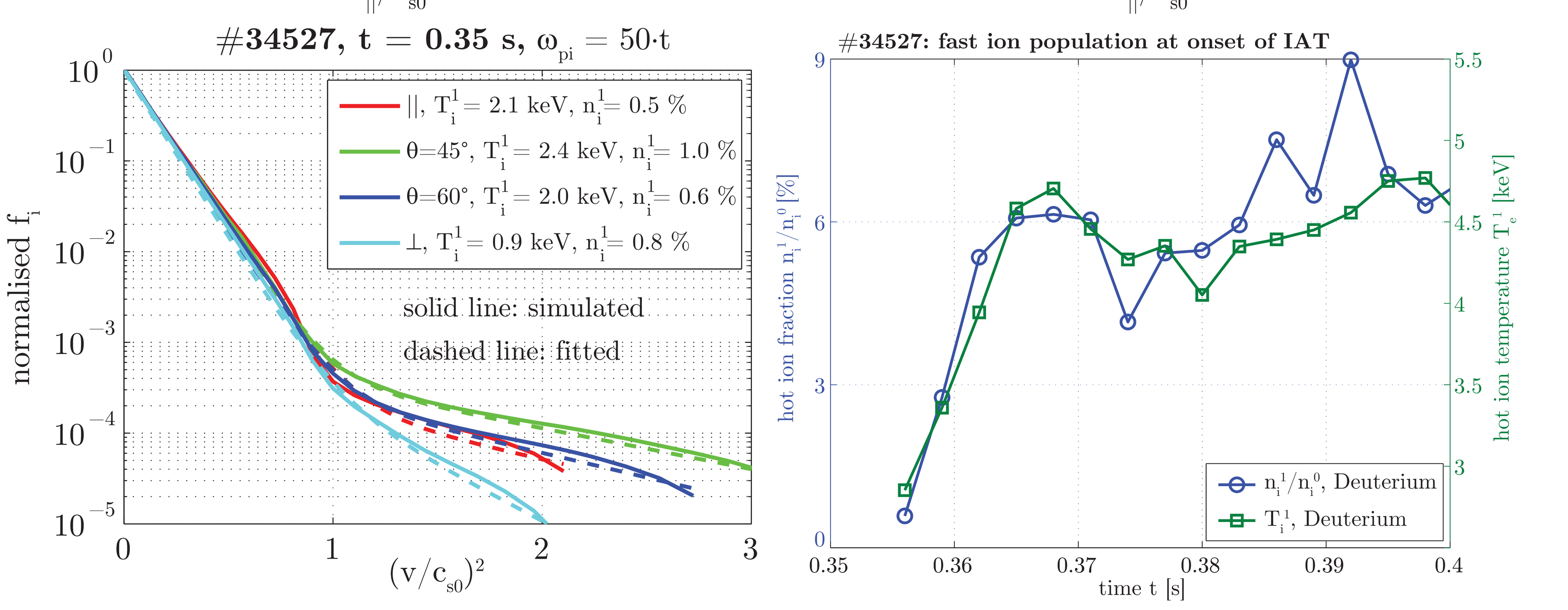


Growth rate during quasi-linear quasi-saturation



Cross-field energization of the ions





Conclusions, work in progress & outlook

- Fast ion populations comprising $\lesssim 30$ % of the ions with perpendicular temperatures up to 5 keV are observed on TCV during ECCD. These populations are stationary for constant I_{ECCD}.
- Numerical modeling shows that IAT develops in these discharges.
- ECCD driven IAT may qualitatively explain the generation of suprathermal ion populations.
- We plan to measure the fluctuation spectrum using an antenna in the plasma periphery.
- The CNPA is being upgraded for off-radial (30°) neutral spectrometry to study the anisotropy of the suprathermal ion tail. The suprathermal population is expected to be hotter in this direction.
- The current code has to be completed to include a correct description of the electron dynamics.
- Future investigation: Fast ion acceleration is also observed upon sawtooth-crashes.