Turbulent transport of MeV range cyclotron heated minorities as compared to fusion alphas

István Pusztai[1], George J. Wilkie[1], Ian G. Abel[2], William Dorland[3], Yevgen O. Kazakov[4], Tünde Fülöp[1]

[1] Department of Physics, Chalmers University of Technology, Göteborg, Sweden [2] Princeton Center for Theoretical Science, Princeton, NJ, USA
[3] Department of Physics, University of Maryland, College Park, MD, USA [4] Laboratory for Plasma Physics, LPP-ERM/KMS, Brussels, Belgium

Summary

Energetic ions from various sources may be considered to mimic alpha particles, such as those generated using ion cyclotron resonance heating (ICRH) in the three-ion minority scheme. We use gyrokinetic tools handling non-Maxwellian species and coupled radial-energy transport simulations to study the effect of turbulent transport on energetic ions. Our results indicate that heated ions are more sensitive to turbulence effects than injected ions.

Motivation

- The confinement of fusion generated alphas is crucial in a reactor.
- To mock up fusion alphas in ITER, ~MeV ions are needed.
- How do the dynamics of heated and injected species compare?
- Collisional slowing down and radial transport can compete [1].

The three-ion minority heated species

- Three-ion minority ICRH scheme [2]: At some suitable concentration ratio of the two main species, the third **trace species** can absorb almost all the coupled power and be energized into the **MeV range**.
- Profiles based on projected plasma parameter profiles of a hybrid ITER scenario, 20020100 of [3], with modified ion composition: 70% $^1\mathrm{H}$, 15% $^4\mathrm{He}$, and 0.1% $^3\mathrm{He}$ as heated minority.
- TORIC [4] ICRH modeling with $B = 5.3\,\mathrm{T}$, $f_{\mathrm{ICRF}} = 50\,\mathrm{MHz}$, $n_{\mathrm{tor}} = 27$ shows strong localized power absorption by $^3\mathrm{He}$ at $r/a \approx 0.25$. Here we use the simulated absorption profile in [5] or a Gaussian model with a peak power density $0.14\,\mathrm{MW/m^3}$ and a width of $0.025a$.

Gyrokinetic transport of trace, non-Maxwellian species

- The pitch angle averaged low collisionality transport equation

$$\frac{\partial F_0}{\partial t} - \frac{1}{V'}\frac{\partial}{\partial r}\left(V'\Gamma_r\right) - \frac{1}{v^2}\frac{\partial}{\partial v^2}\left(v^2\Gamma_v\right) = C\left[F_0\right] + H\left[F_0\right] + S. \qquad (1)$$

- **Energy resolved** turbulent **fluxes** for a trace species

$$\Gamma_r = -D_{rr}\frac{\partial F_0}{\partial r} - D_{rv}\frac{\partial F_0}{\partial v}, \qquad \Gamma_v = -D_{vr}\frac{\partial F_0}{\partial r} - D_{vv}\frac{\partial F_0}{\partial v}. \qquad (2)$$

- $D_{xx}(v,r)$ **from nonlinear** GS2 [6] (*alphas* branch [7]) **simulations**.
- H is a quasilinear heating term as used by Stix [8].
- Perturbative approach: F_0 is from balancing collisions with heating or sources. Breaks down in the realistic case of $\partial_r\Gamma_r \sim C[F_0]$.
- Self-consistent approach: Solve transport equation, (1) and (2), in radius and energy using T3CORE [9].

Heated minorities vs fusion alphas; perturbative treatment

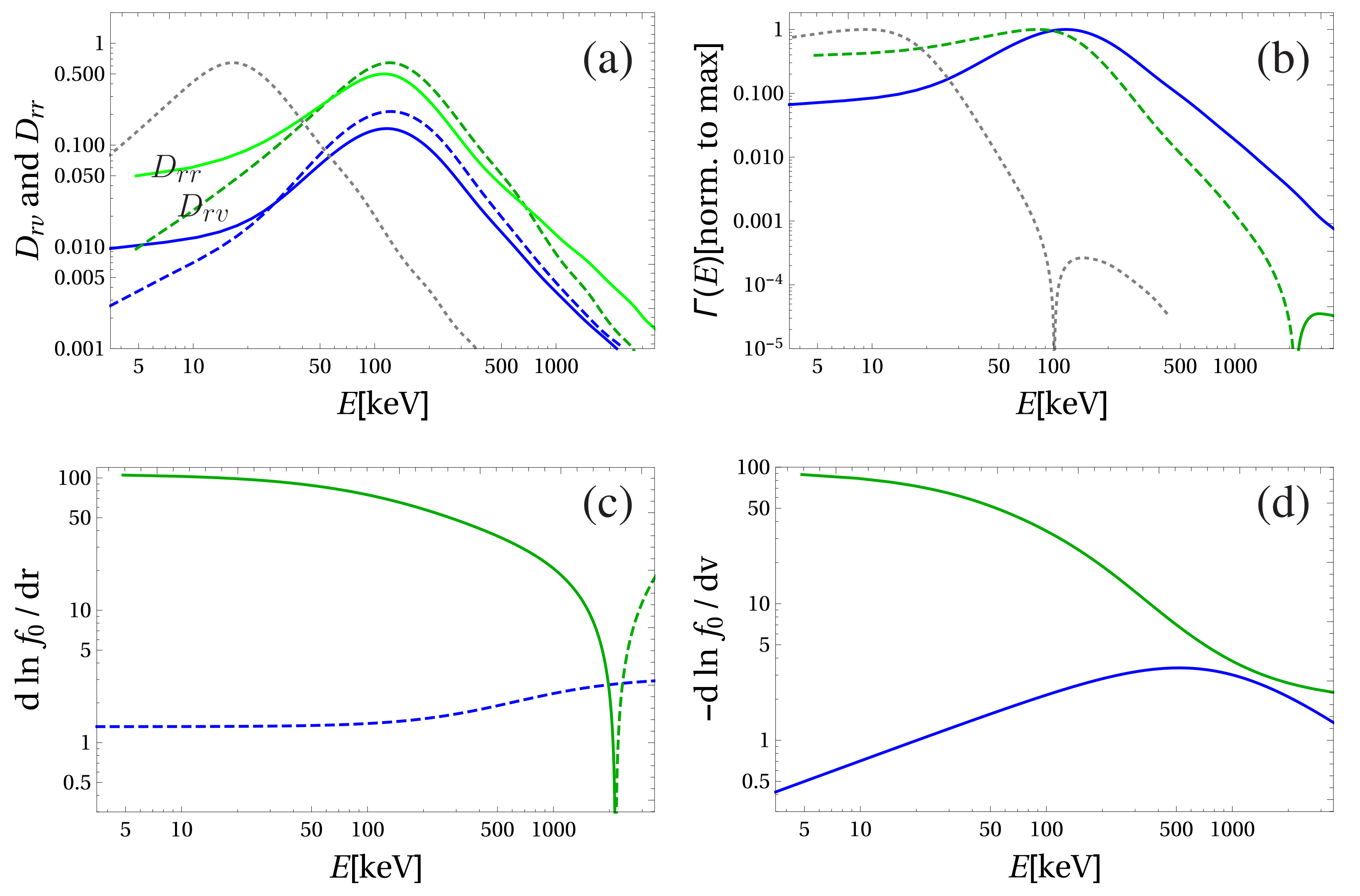

Figure 1: Transport coefficients (a), radial particle flux (b), and logarithmic radial- (c) and speed (d) derivatives of the distribution functions of the energetic minority. The calculations are based on ITER scenario 20020100 at $\rho = 0.275$. Blue curves: α slowing-down distribution, α-source and turbulence calculated for $50-50\%$ D-T. Green curves: ICRF heated ^{3}He in $^1\mathrm{H} + ^4\mathrm{He}$ plasma (same with reduced temperature and density shown in grey). Dashed lines represent negative values.

- First we neglect turbulence effects on the hot ion distribution.
- Heated minority is approximated with an isotropic distribution, (33) of Ref. [8]. For alphas a slowing down distribution is assumed.
- Transport peaks at $E \sim 4T_i$ and transport coefficients are similar.
- α transport outward due to radially decreasing source density.
- **Heated species transports into location of strong heating**.

Heated and injected ions; transport modeling

- **Heated ions can be removed by radial transport before reaching high energies**; injected ions are less sensitive to turbulence.
- Predicted **density pinch** [5] against the fast ion temperature gradient is **confirmed**, when high temperature can develop.

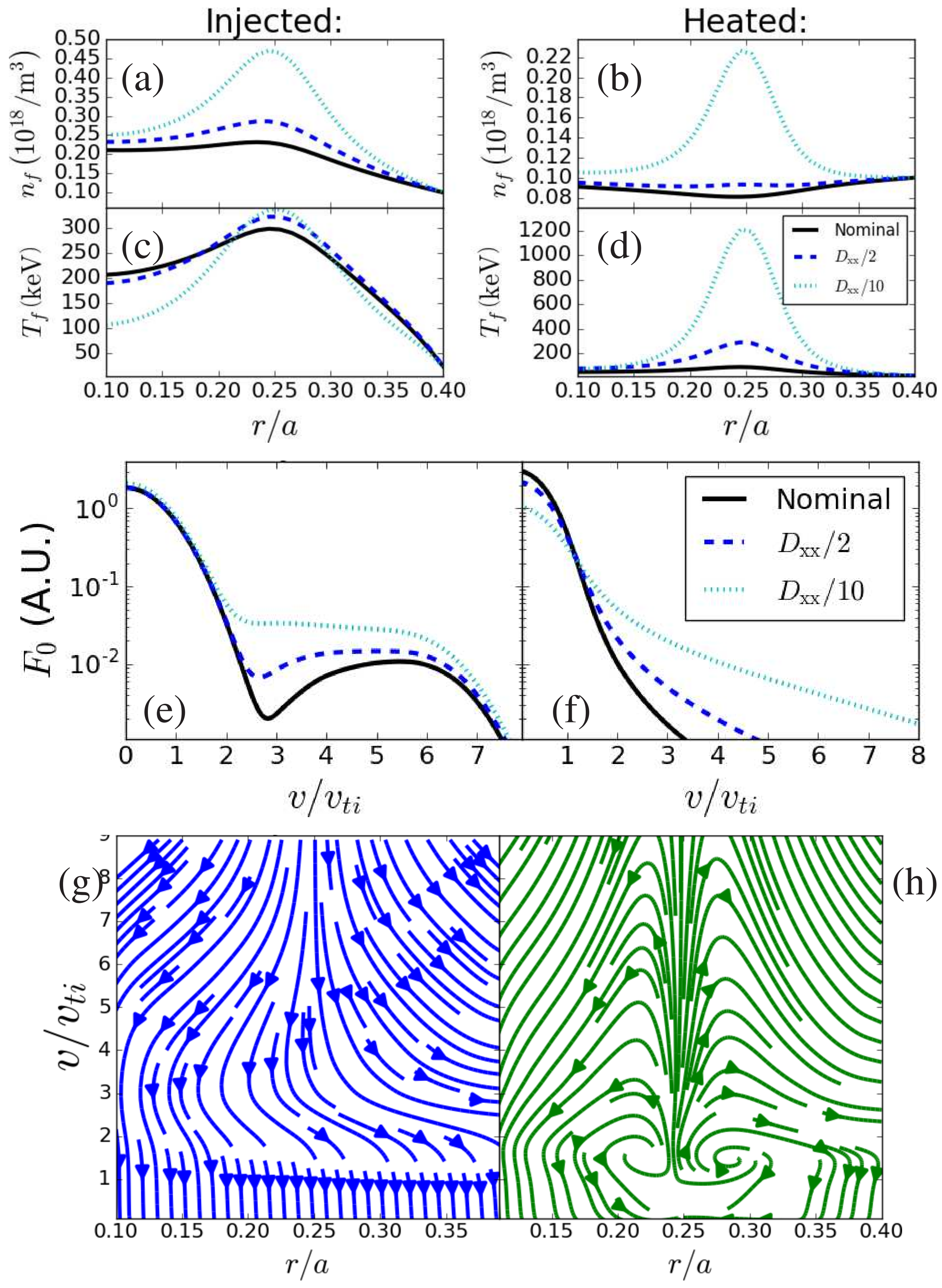

Figure 2: Density (a,b), temperature (c,d), speed distribution at $r/a = 0.25$ (e,f), and phase space flux stream plots for $D_{xx}/10$ case (g,h). (a,c,e,g): ^{1}H ions injected at $1\,\mathrm{MeV}$ with a power deposition profile similar to that of the ICRH minority ^{3}He of (b,d,f,h). Line styles indicate turbulence intensity in (a-f). Nominal case is strongly driven ITG; weaker turbulence is expected.

Conclusions

- **The *alphas* branch of GS2 and T3CORE provide a framework to study the coupled radial-energy transport of energetic, non-Maxwellian ion species, with turbulence, collisions and sources.**
- **Distribution of a heated species is globally more sensitive to turbulence; it can develop a tail when turbulence intensity is sufficiently low. Accumulation in the region of absorption.**
- **Hot tail of injected species and alphas are less sensitive to turbulence; they may develop inverted energy distributions in superthermal range where radial transport competes with collisions.**

References

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