Gyrokinetic simulations of microturbulence in TCV electron internal transport barriers

X. Lapillonne[1], S. Brunner[1], O. Sauter[1], L. Villard[1], T. Görler[2], F. Jenko[2] and F. Merz[2]

[1]Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas,
Association Euratom-Confédération Suisse, CH-1015 Lausanne, Switzerland
[2] Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, D-85748 Garching, Germany

Introduction / Motivation

- Internal Transport Barriers (ITB's) are regions of reduced outward radial energy and/or particle transport in the core plasma.
  $\Longrightarrow$ Increased density and temperature gradients compared to standard discharges.
  $\Longrightarrow$ ITB's may provide an approach for achieving high performance regimes in fusion reactors.
- Electron Internal Transport Barriers (eITB's) have been systematically obtained in the TCV tokamak [1] leading simultaneously to sharp density and electron temperature gradients.
- A quasi-linear study [2] has shown that for typical density and temperature gradients measured in eITB barriers, the fluctuation spectra simultaneously contains Trapped Electron Modes (TEM's) and Ion Temperature Gradient (ITG) modes whose contributions to the electron particle flux are respectively outward/inward and cancel each other out. This mechanism, enabling a zero turbulent particle flux, may play an essential role for explaining the existence of eITBs.

Goal

- Validate quasi-linear prediction of zero particle flux ($\Gamma = 0$) conditions through non-linear gyrokinetic simulations using the local (flux-tube) version of the GENE code [3].
- Compare the physical parameters for achieving $\Gamma = 0$ in the simulations with experimental values measured in TCV eITB's.
- Compare as well the level of electron heat transport.

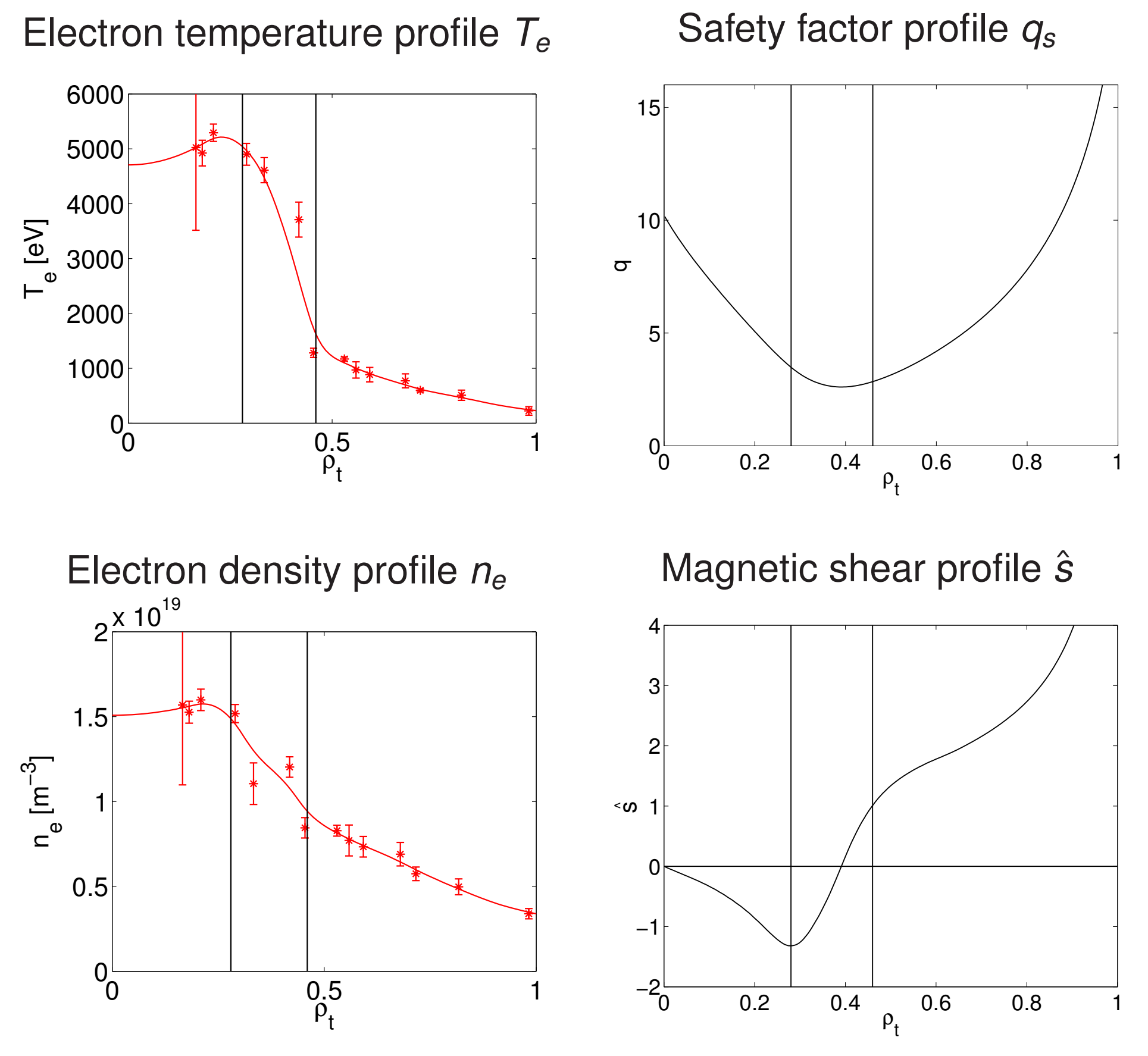
Simulation Model: Gyrokinetic GENE code

- Eulerian-based gyrokinetic code, enabling non-linear simulations of microturbulence in magnetic confinement devices.
- Multi-species kinetic dynamics, electrostatic and electromagnetic fluctuations, linearized self- and inter-species collisions.
- Generalized from a flux-tube to a global geometry [4][5], including radial variation of profiles (density, temperature, geometrical coefficients), non-periodic radial boundaries, particle and heat sources/sinks.
- Interface to MHD equilibrium codes such as CHEASE [6].

e-ITB's in the TCV Tokamak

- **TCV tokamak:**
  major radius $R = 0.88m$, minor radius $a = 0.24m$ (mid-plane), magnetic field on axis $B_0 = 1.44T$
- **TCV discharge #29866 depicting a typical eITB in Deuterium plasma.**

- Barrier region: $0.28 \lesssim \rho_t \lesssim 0.46$
  $\rho_t = \sqrt{\phi_t/\phi_{t,\text{edge}}}$, ϕ_t = toroidal flux.
- Measured gradients in eITB:
  $R/L_{Te} = 10 - 30$
  $R/L_{ne} = 3 - 10$
  R/L_{Ti} unknown
  $L_{T,n}$ = characteristic gradient length of temperature/density.
- $\tau = T_e/T_i = 3.5$
  $Z_{\text{eff}} = 2$, Carbon as dominant impurity.
- Magnetic shear inversion ($\hat{s} = 0$) within barrier at $\rho_t \simeq 0.4$.



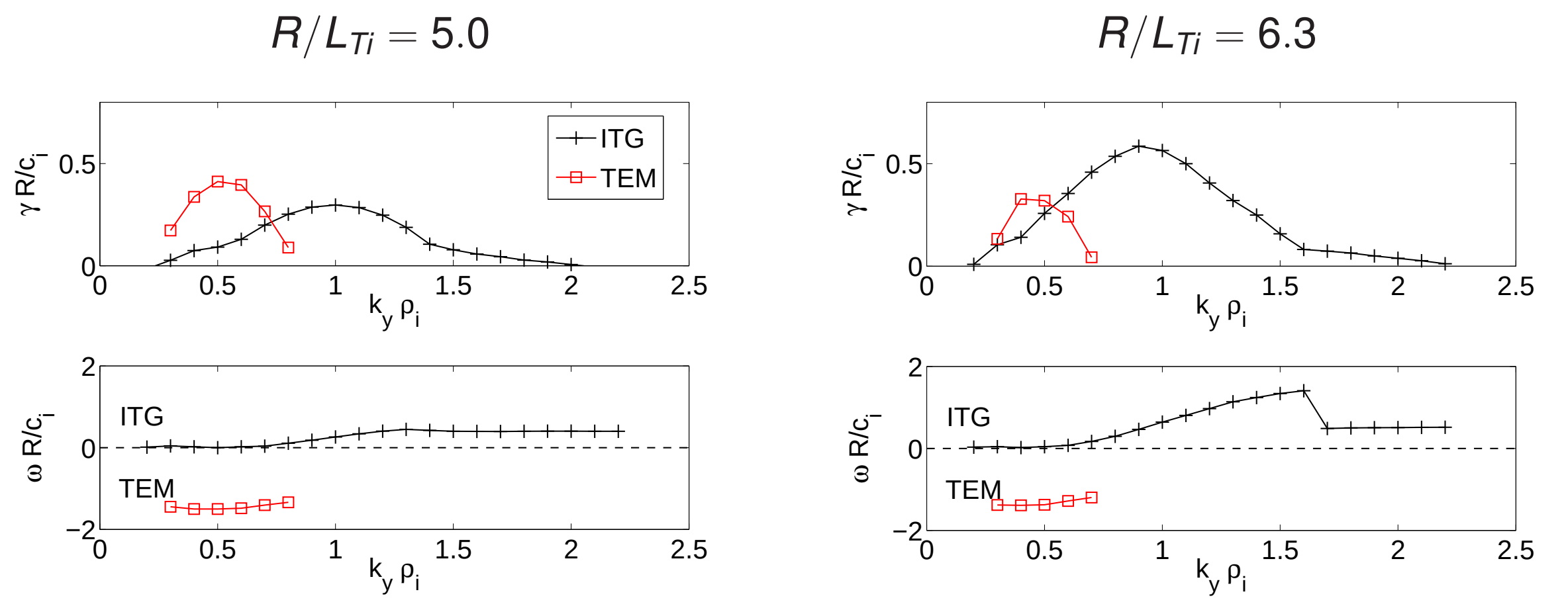
Flux-tube simulations carried out for physical parameters at $\rho_t = 0.3$:

- CHEASE equilibria with $q_s = 3.2$, $\hat{s} = -1.17$, and $r/R = 0.09$.
- Three kinetic species with real mass ratios: Electron (e), Deuterium (D), Carbon (C)
  $\tau = T_e/T_i = 3.5$ with $T_D \equiv T_C \equiv T_i$ assumed
  $n_D/n_e = 0.8$ and $n_C/n_e = 0.03 \longrightarrow Z_{\text{eff}} = 2$
  $R/L_{Te} = 12$ and $R/L_{T,D} = R/L_{T,C} = R/L_{Ti} = 2 - 10$ (scanned)
  $R/L_{ne} = 3$, $R/L_{n,D} = 3.4$, and $R/L_{n,C} = 1.5$ (consistent with quasineutrality).
- Collisionality $\nu_e^\star = 5.6 \cdot 10^{-2}$ consistent with experimental values.
- $\beta = 10^{-4}$ (experimental value $\beta \simeq 10^{-2}$) $\Longrightarrow$ Essentially electrostatic fluctuations.

Note: $Te/Ti > 1$ as well as $Z_{\text{eff}} > 1$ both have a stabilizing effect on the very short wavelength Electron Temperature Gradient (ETG) modes, which thus did not need to be accounted for in the simulations.

Linear Simulations

Frequency ω and growth rate γ



- Two most unstable eigenmodes computed for each k_y with eigensolver version of GENE.
- The unstable spectra simultaneously contains longer wavelength TEM modes (negative frequency, $k_y\rho_i < 0.5$) and shorter wavelength ITG modes (positive frequency, $k_y\rho_i > 0.5$).
- Going from $R/L_{Ti} = 5.0$ to $R/L_{Ti} = 6.3$ the most unstable mode changes from TEM to ITG.

Quasi-Linear Study

Model for Quasi-Linear Fluxes $F = \Gamma, Q$

$$F^{q.l.} = \sum_{k_y} \hat{F}^{q.l.}_{k_y} \Delta k_y \,,$$

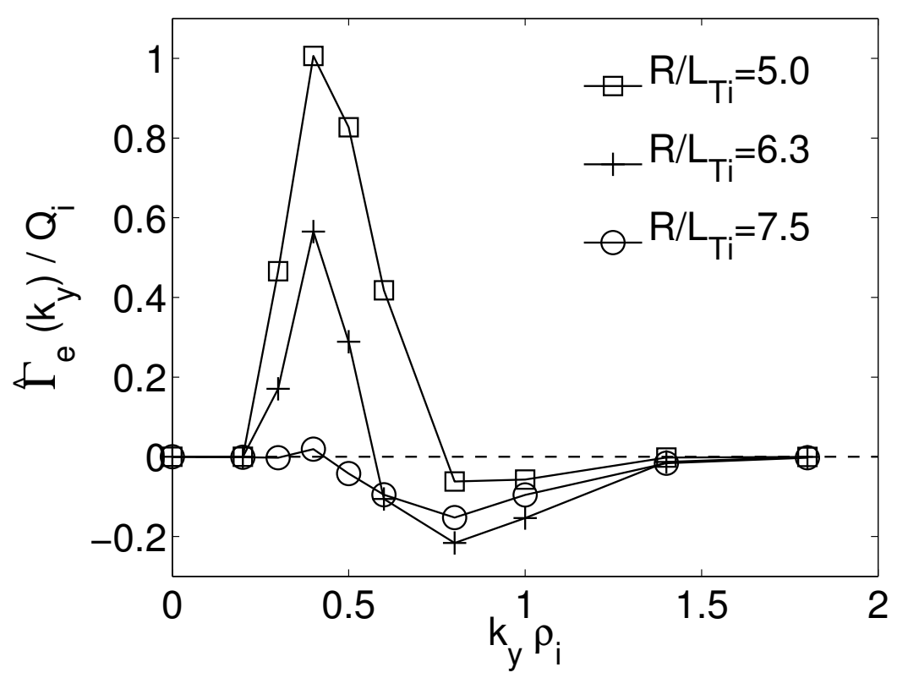
$$\hat{F}^{q.l.}_{k_y} = A(k_y) \frac{\hat{F}_{k_y}}{|\hat{\Phi}_{0,k_y}(0)|^2} \,,$$

with the spectral amplitude weighting model

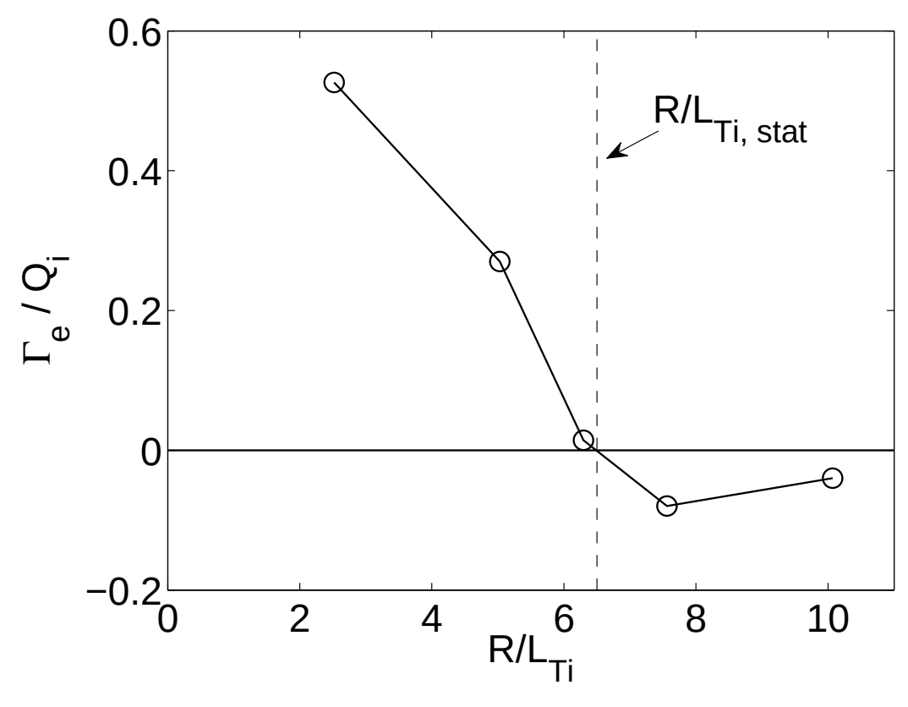
$$A(k_y) = A_0 \left(\frac{\gamma_{k_y}}{\langle k_\perp^2 \rangle} \right)^\xi \,, \text{ here } \xi = 2,$$

$\hat{F}_{k_y}$, $\hat{\Phi}_{0,k_y}(0)$, and $\langle k_\perp^2 \rangle$ from linear GENE simulations.

Electron particle flux spectra $\Gamma_e(k_y)$
for different R/L_{Ti}



Electron particle flux Γ_e vs. R/L_{Ti}

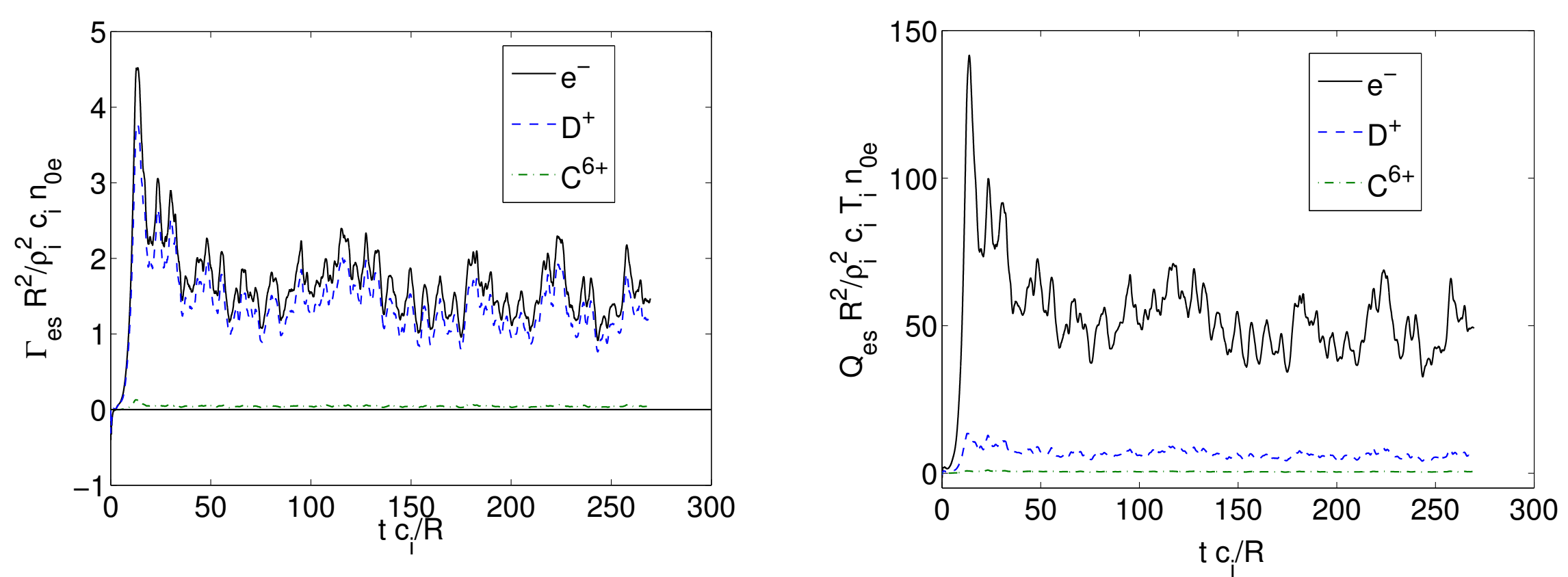


- Spectral analysis: Outward (resp. inward) particle flux contributions at lower (resp. higher) k_y values, where TEM (resp. ITG) modes are most unstable.
- Effectively outward (resp. inward) flux at low (resp. high) R/L_{Ti}, i.e. when TEM (resp. ITG) is overall most unstable mode.
- Stationary state ($\Gamma_e = 0$) for $R/L_{Ti} = R/L_{\text{Ti,stat}} \simeq 6$.

stephan.brunner@epfl.ch

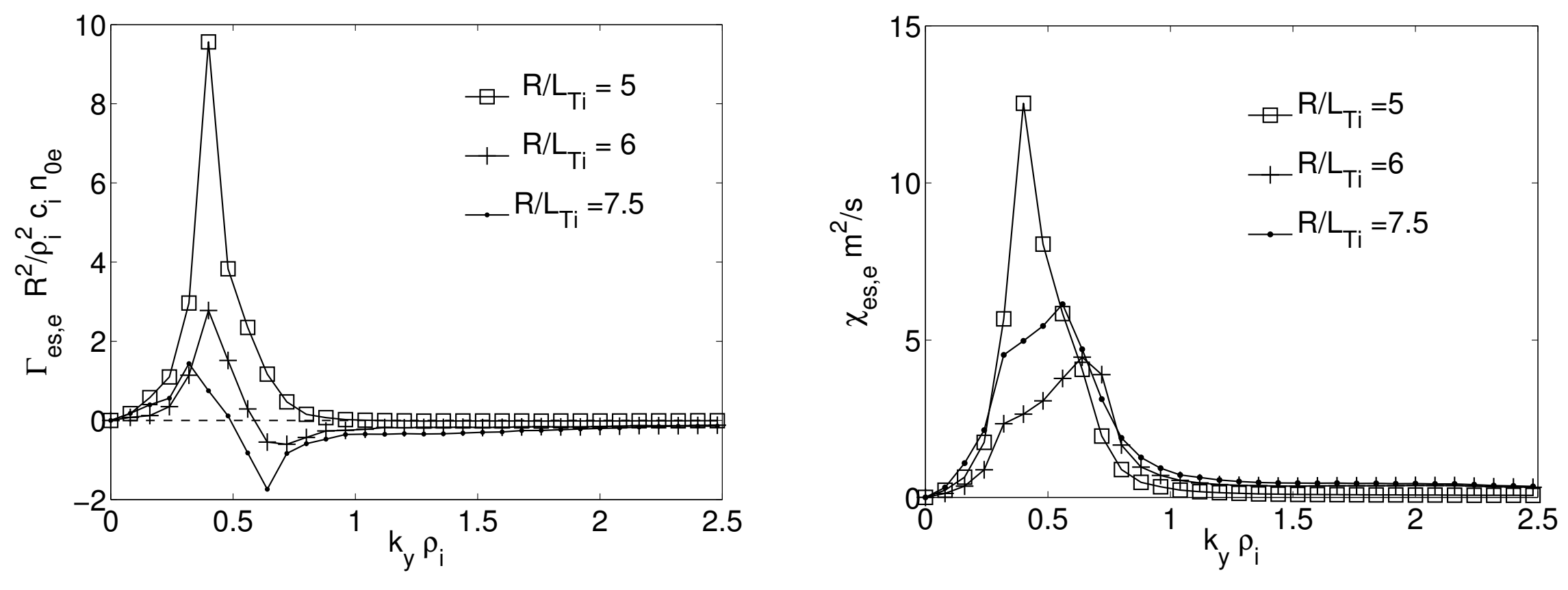
Non-Linear Simulations

Particle fluxes Γ and heat fluxes Q vs. time for $R/L_{Ti} = 5$

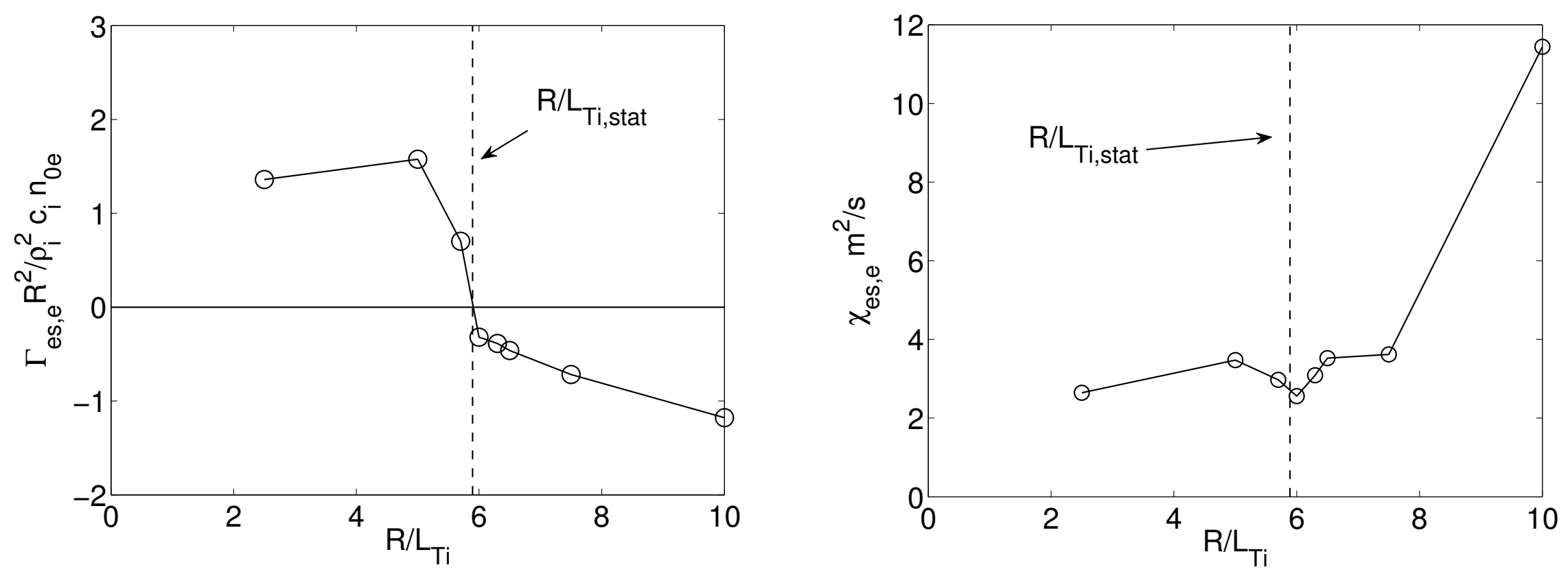


- TEM is the most unstable linear mode for $R/L_{Ti} = 5$
  $\Longrightarrow$ Outward electron particle flux, in agreement with quasi-linear estimate.
  $\Longrightarrow$ Electron heat flux dominates ion heat fluxes.
- Ambipolarity satisfied in all cases: $\Gamma_{es,D} + Z_C\Gamma_{es,C} = \Gamma_{es,e}$

Electron Particle flux spectra $\Gamma_e(k_y)$
and heat diffusivity spectra $\chi_e(k_y)$ for different R/L_{Ti}



Electron Particle flux Γ_e and heat diffusivity χ_e vs. R/L_{Ti}



- Non-linear results validate quasi-linear model estimates at different R/L_{Ti} for electron particle fluxes, including detailed spectral features.
  In particular, stationary state ($\Gamma_e = 0$) at $R/L_{\text{Ti,stat}} \simeq 6$ confirmed.
- Non-linear R/L_{Ti} scan presents minimum of electron heat diffusivity at $R/L_{\text{Ti,stat}}$. Probably results from non-linear interaction between ITG and TEM modes. Similar effect observed in Ref. [7].
- Diffusivity from simulation at $\Gamma_e = 0$: $\chi_e(R/L_{\text{Ti,stat}}) \simeq 2\, m^2/s$.
  Experimental diffusivity measured in barrier region: $\chi_e^{\text{exp}} \simeq 1\, m^2/s$

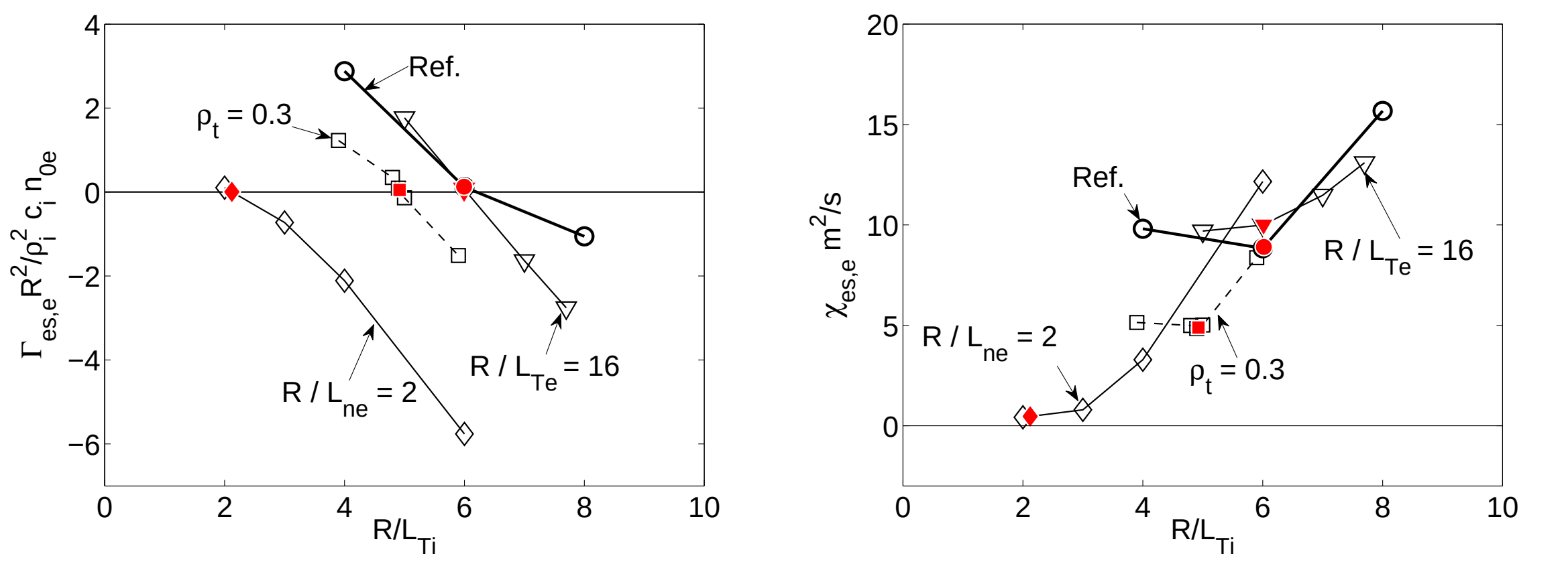
References :

[1] O. Sauter *et al.*, *Phys. Rev. Lett. 94*, 105002 (2005).
[2] E. Fable, C. Angioni, and O. Sauter, *Plasma Phys. Control. Fusion 52*, 015007 (2010).
[3] F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers, *Phys. Plasmas 7*, 1904 (2000).
[4] T. Görler, Ph.D. thesis, University of Ulm, Germany, 2009.
[5] X. Lapillonne, Ph.D. thesis, EPFL, Switzerland (2010).
[6] H. Lütjens, A. Bondeson, and O. Sauter, *Comp. Phys. Comm. 97*, 219, (1996).
[7] F. Merz and F. Jenko, *Nucl. Fusion 50*, 054005 (2010).

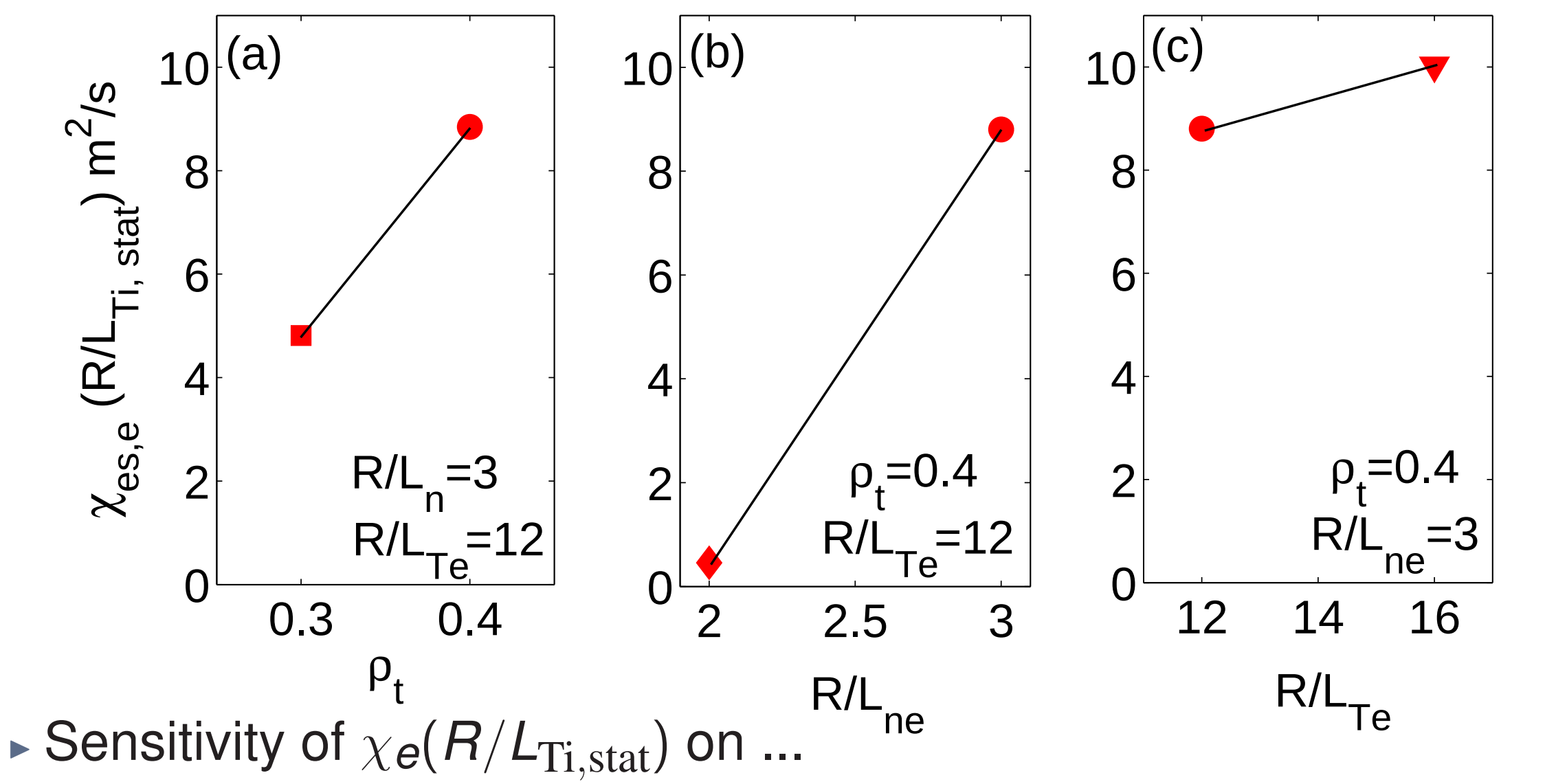
Sensitivity of Electron Heat Transport on eITB Background Parameters

- Previous simulations considered relatively low values of R/L_{ne} and R/L_{Te} compared to experiment and only a single radial position ρ_t was analyzed.
  $\Longrightarrow$ How sensitive is $\chi_e(R/L_{\text{Ti,stat}})$ with respect to these electron profile gradients and to local magnetic geometry varying with ρ_t?
- Sensitivity study carried out for slightly different magnetic configuration, such that at ...
  $\rho_t = 0.3$: $q_s = 9$, $\hat{s} = -0.55$, $r/R = 0.09$
  $\rho_t = 0.4$: $q_s = 7$, $\hat{s} = -1.22$, $r/R = 0.12$
  Otherwise, physical parameters same as before for reference case.
- R/L_{ne}, R/L_{Te} and ρ_t individually varied wrt. reference values $R/L_{ne} = 3$, $R/L_{Te} = 12$, $\rho_t = 0.4$.

Electron particle flux Γ_e and heat diffusivity χ_e vs. R/L_{Ti}
Stationary state ($\Gamma_e = 0$) pointed out in red.



Summary: Electron heat diffusivity χ_e at $\Gamma_e = 0$ as a function of (a) flux tube position ρ_t, (b) electron density gradient R/L_{ne}, and (c) electron temperature gradient R/L_{Te}



- Sensitivity of $\chi_e(R/L_{\text{Ti,stat}})$ on ...
  (a) Position ρ_t : moderate, (b) R/L_{ne}**: strong**, (c) R/L_{Te}: weak.

Conclusions

- Non-linear flux-tube simulations confirm the interplay mechanism predicted by the quasi-linear model between TEM and ITG modes which may lead to $\Gamma_e = 0$.
- Quantitative agreement between simulations and quasi-linear model for estimating critical ion gradient $R/L_{\text{Ti,stat}}$ where $\Gamma_e = 0$.
- Corresponding electron heat diffusivity $\chi_e(R/L_{\text{Ti,stat}})$ from flux-tube simulations appears however to be significantly larger than experimentally measured.
- Preliminary global non-linear simulations show a significant reduction ($\sim$ factor 10) of χ_e due to finite $\rho^\star$ effects ($\rho^\star \simeq 1/100$ in TCV).

Theory of Fusion Plasmas, Varenna, Aug. 30 - Sept. 3, 2010