7th Asia Pacific Transport Working Group International Conference

Turbulent Particle Transport in Transport Barriers

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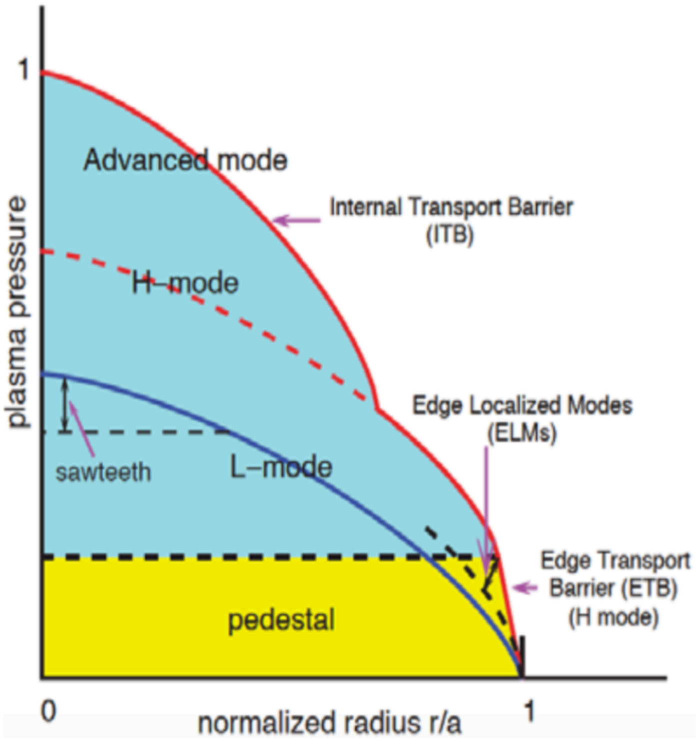
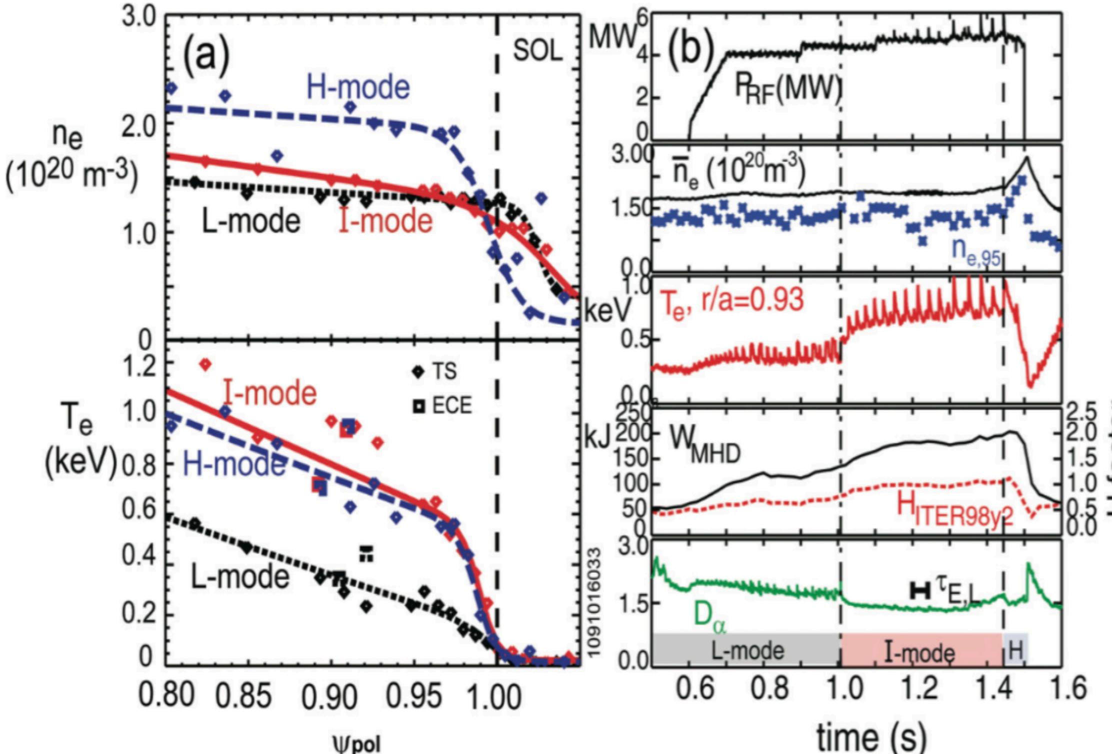
Outline

- **Background**
- **Physical Model and Equation**
- **Numerical Results**
  - Multiple TEMs and ITG modes in transport barriers
  - Quasi-linear mixing length estimation
  - Quasi-linear particle transport estimation
- **Summary**

Background: Transport Barriers

- ✓ Transport Barriers
  1. Edge Transport Barrier
  2. Internal Transport Barrier

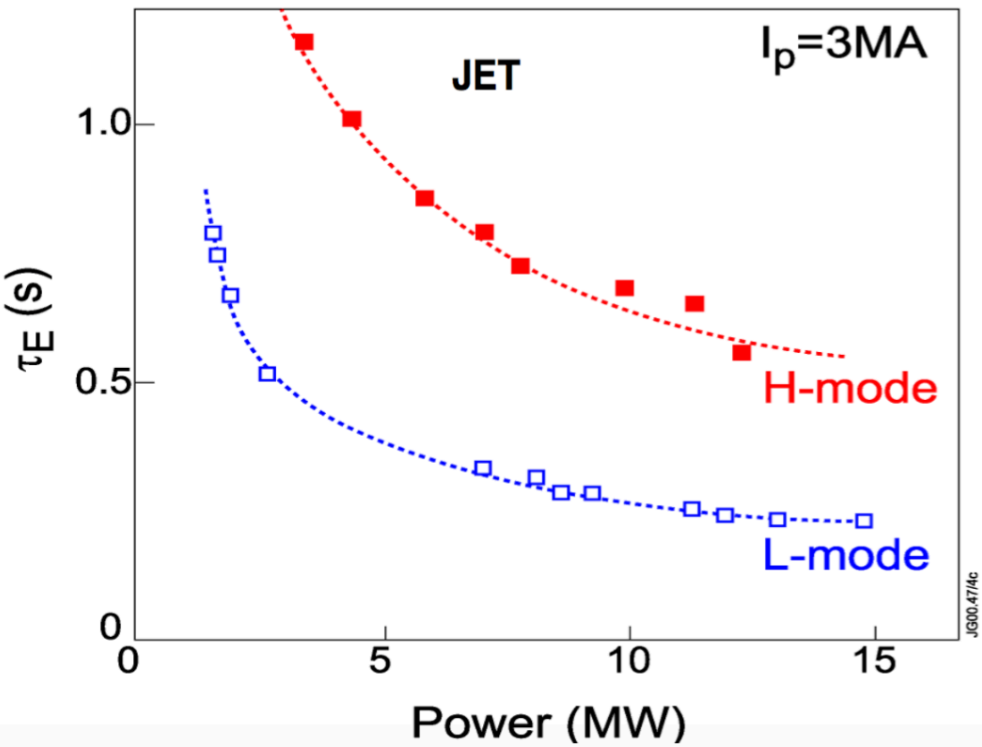


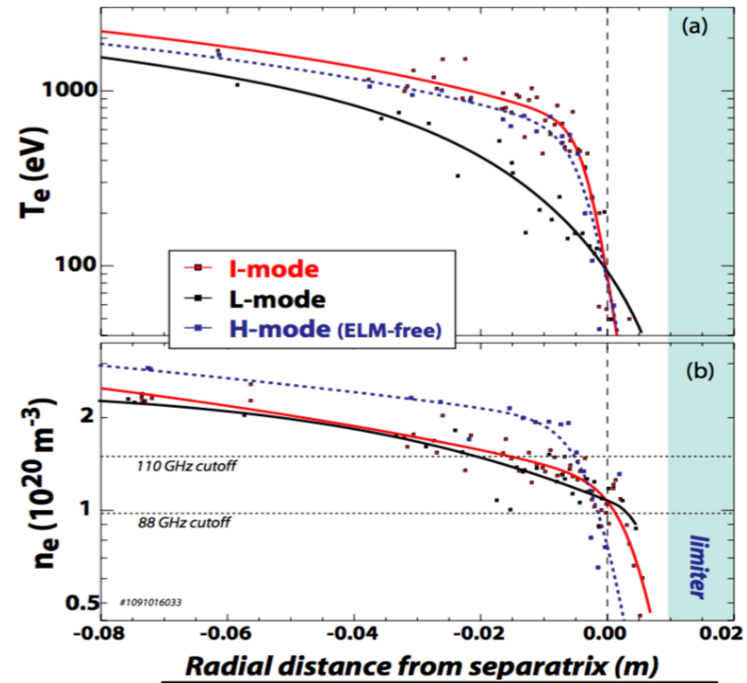


A. E. Hubbard et al POP 2011

Background: H-mode, I-mode and L-mode

- ✓ H-mode : Steep temperature and density gradients in pedestals.
- ✓ I-mode : Steep temperature gradient comparable to H-mode and density gradient comparable to L-mode.
- ✓ L-mode : Medium temperature and density gradients.

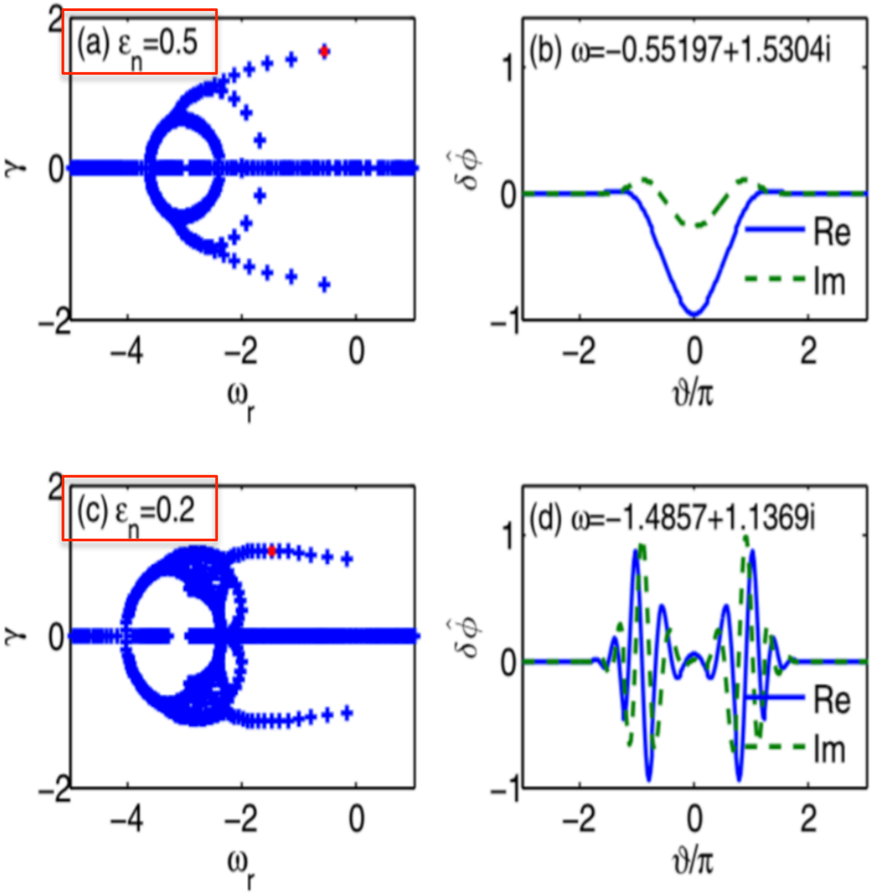




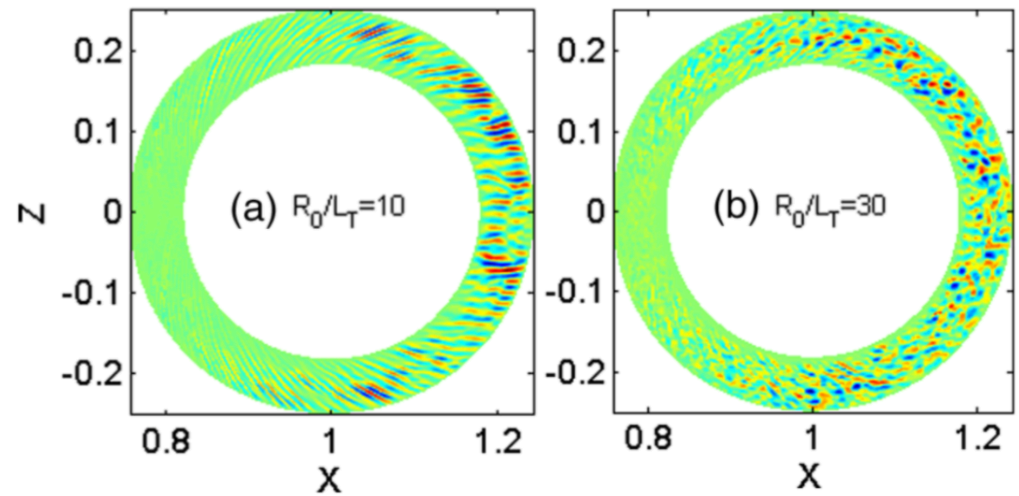
D.G. Whyte et al NF 2010

Background： Unconventional Structures and Streamer

Conventional ballooning structure



Unconventional ballooning structure



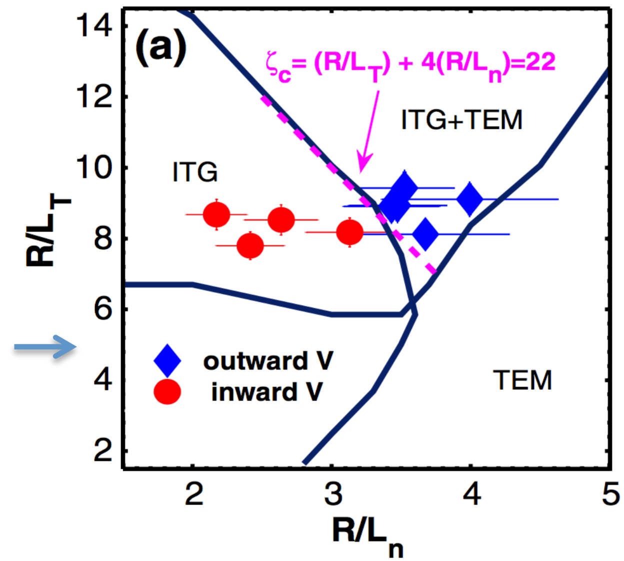
Two-dimensional turbulence intensity in the poloidal plane for nonlinearly weak and strong gradients

H. S. Xie et al POP 2015

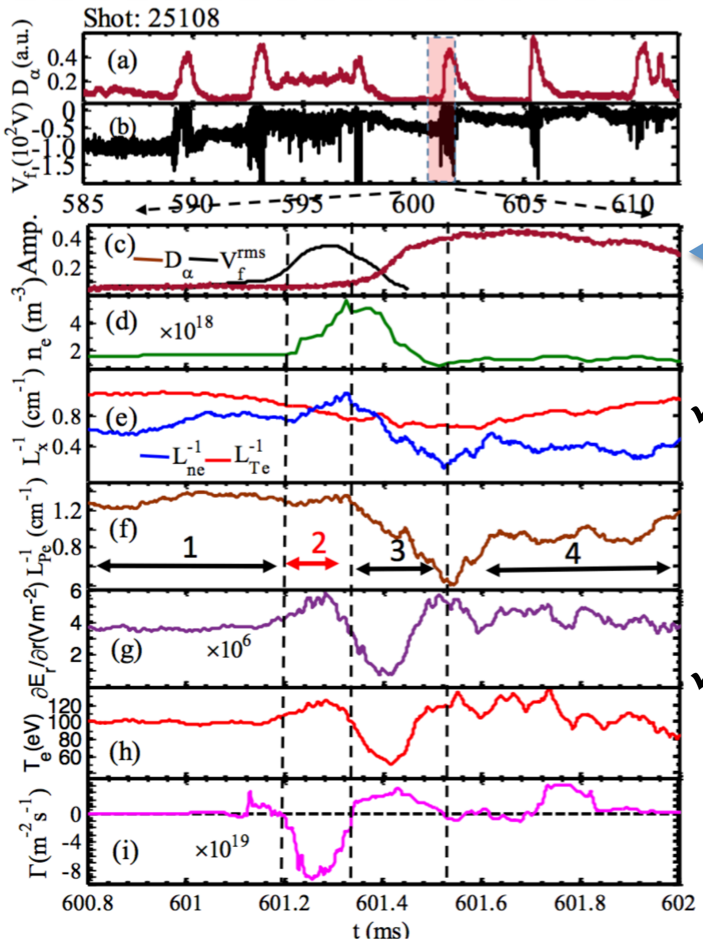
H. S. Xie, Y. Xiao and Z. H. Lin PRL 2017

Background: Simulations Agree with the Experimental Results

✓ Agreement between the experimental results and the quasilinear gyrokinetic simulation is qualitatively satisfactory.



Tore Supra tokamak



HL_2A

✓ A quasi-coherent mode was observed in the transport barrier in edge region of H-mode plasmas in tokamaks as a precursor to ELM crash.

✓ Typical parameters: $\eta_i = 0.80,\ k_\theta\rho_s = 0.6,\ q = 3,$
$\hat{s} = 1.6,\ \eta_e = 0.80,\ \varepsilon_n = 0.048,$
$\tau = 1.25,\ \varepsilon = 0.23$

J. Cheng et al PRL 2013

W. L. Zhong et al PRL 2013

Physical Model and Equation

- ✓ The ballooning representation
- ✓ The $s-\alpha$ equilibrium model with circular flux surfaces (here $\alpha=0$)
- ✓ The electron is adiabatic and the ion is nonadiabatic
- ✓ The non-adiabatic response h is determined by

$$\boxed{i\frac{v_{//}}{qR}\frac{\partial}{\partial\theta}h_s+\left(\omega-\omega_{Ds}\right)h_s=\left(\omega-\omega_{*sT}\right)J_0\left(\alpha_s\right)F_{Ms}\frac{q_s n_0}{T_s}\hat{\phi}(\theta)}$$

FLR effect

$$k_{//}v_{//} \qquad \omega_{Di}=2\tau_e^{-1}\varepsilon_n\left(\cos\theta+\hat{s}\theta\sin\theta\right)\left(\frac{\hat{v}_\perp^2}{2}+\hat{v}_{//}^2\right) \qquad \omega_{*T}=-\tau_e^{-1}\omega_{*e}\left[1+\eta_i\left(\hat{v}_\perp^2+\hat{v}_{//}^2-\frac{3}{2}\right)\right]$$

Landau resonance/damping: $\dfrac{1}{\left(\omega-\omega_{Di}-k_{//}v_{//}\right)}$

Physical Model and Equation - ITG

The integral eigenmode equation from quasineutrality condition

$$(1+\tau_e)\hat{\phi}(k)=\int_{-\infty}^{+\infty}\frac{dk'}{\sqrt{2\pi}}K(k,k')\hat{\phi}(k')$$

$$K(k,k')=-i\int_{-\infty}^{0}\omega_{*e}d\tau\frac{\sqrt{2}e^{-i\omega\tau}}{\sqrt{a}(1+a)\sqrt{\lambda}}e^{-\frac{(k-k')^2}{4\lambda}}\Gamma_0(k_\perp,k'_\perp)$$

$$\times\left[\frac{\omega\tau_e}{\omega_{*e}}+1-\frac{3\eta_i}{2}+\frac{2\eta_i}{(1+a)}\left(1-\frac{k_\perp^2+k_\parallel^2}{2(1+a)\tau_e}+\frac{k_\perp k_\parallel}{(1+a)\tau_e}\frac{I_1}{I_0}\right)+\frac{\eta_i(k-k')^2}{4a\lambda}\right]$$

Typical parameters adopted:

$$\eta_i=0.80,\ k_\theta\rho_s=0.6,\ q=3,$$
$$\hat{s}=1.6,\ \eta_e=0.80,\ \varepsilon_n=0.048,$$
$$\tau=1.25,\ \varepsilon=0.23$$

✧ Updated HD7 code

- For quasi-linear mixing length estimation
- For quasi-linear turbulent particle flux estimation

Physical Model and Equation - TEM

✓ Neglect the finite Larmor radius effect of trapped electrons

✓ The perturbation of trapped electron density

$$\tilde{n}_{et} = -\frac{e n_e}{T_e}\sqrt{\frac{2\epsilon}{\pi}}\int_0^{\infty} dt\sqrt{t}e^{-t}\int_0^1 \frac{\omega-\omega_*^e}{\omega-\overline{\omega}_d^e}\cdot\frac{d\kappa^2}{4F(\kappa)} \times \sum_{j=-\infty}^{+\infty} \underline{g(\theta-2\pi j,\kappa)}\int_{-\infty}^{+\infty} d\theta' \, \underline{g(\theta',\kappa)}\phi(\theta'-2\pi j)$$

The perturbation of TE density are Even Parity

where,

$$g(\eta,\kappa) = \int_{-\theta_r}^{\theta_r} \frac{\delta(\eta-\theta')d\theta'}{\sqrt{\kappa^2-\sin^2(\theta'/2)}}$$

$$\kappa^2 = \sin^2(\theta_r/2)$$

$$\epsilon = r/R$$

$$\eta_e = \frac{L_{ne}}{L_{Te}}$$

$$\overline{\omega}_d^e = \omega_{*_e}\epsilon_n t G(\hat{s},\kappa) = \omega_{*_e}\epsilon_n t\left[\frac{2F(\kappa)}{K(\kappa)} - 1 + 4\hat{s}\left(\frac{F(\kappa)}{K(\kappa)} - (1-\kappa^2)\right)\right]$$

$$\omega_*^e = \omega_{*_e}[1+\eta_e(t-\tfrac{3}{2})]$$

J. Q. Dong et al POP 1997
H. Du et al POP 2014

Physical Model and Equation – Estimate Transport

- ✓ For quasi-linear mixing length estimation

$$\chi_{\mathrm{i}} = \frac{\widehat{\gamma}}{\widehat{k}_{\mathrm{r}}^{2}} \frac{k_\theta \rho_s}{\varepsilon_n} \left(\frac{c_s}{R} \rho_s^2 \right), \qquad \widehat{k}_{\mathrm{r}}^{2} = k_\theta^2 \rho_s^2 \widehat{s}^{\,2} \langle \theta^2 \rangle$$

- ✓ For quasi-linear turbulent particle flux

$$\tilde{n}_i = -\tau_i \left(1 - f_z\right) \hat{\phi} + \int_{-\infty}^{\infty} dk' H_i \left(k, k'\right) \hat{\phi} \qquad v_r = \frac{E_\theta B_\phi - E_\phi B_\theta}{B^2}$$

$$\tilde{n}_z = -\tau_z Z f_z \hat{\phi} + \int_{-\infty}^{\infty} dk' H_z \left(k, k'\right) \hat{\phi} \qquad B_\phi \gg B_\theta, \quad E_\theta \gg E_\phi$$

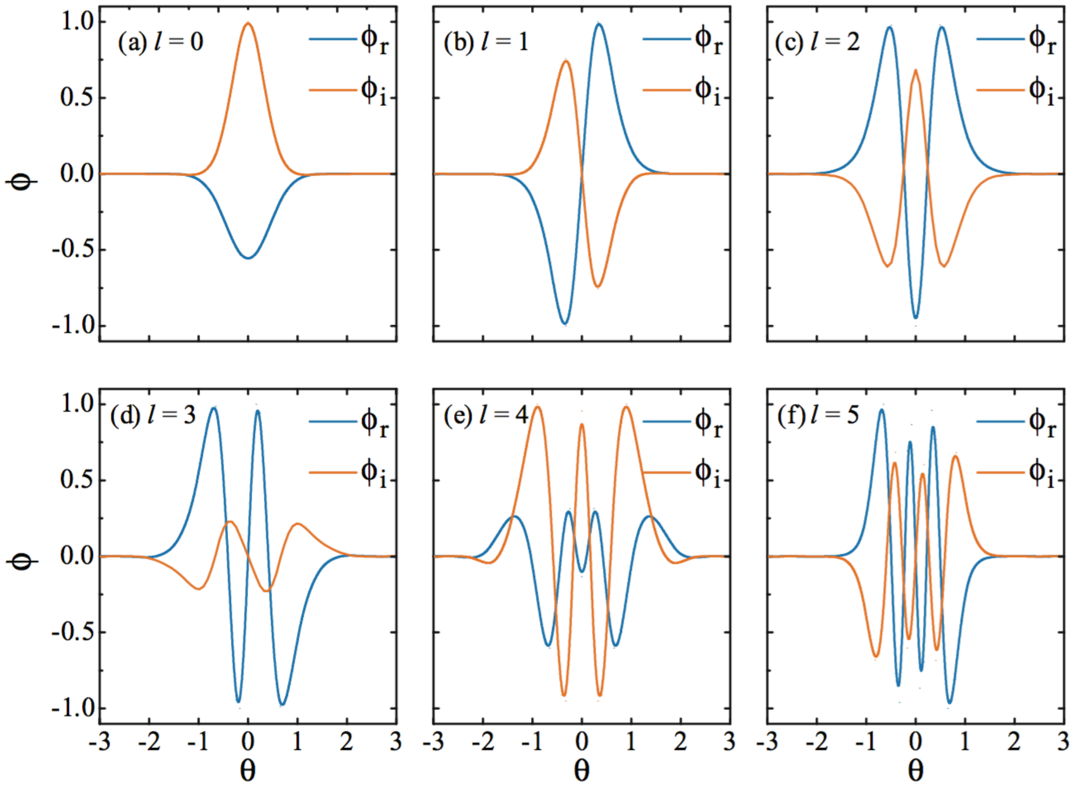
$$\Gamma_i = \hat{\gamma} \left\langle \tilde{n}_i \cdot \tilde{v}_r \right\rangle = \frac{c_s}{2 n_{0e}} \hat{\gamma} k_\theta \rho_s \cdot R_e \sum_k \left\langle \hat{n}_i \cdot \left(-i\tilde{\phi}\right)^* \right\rangle,$$

$$\Gamma_z = \hat{\gamma} \left\langle \tilde{n}_z \cdot \tilde{v}_r \right\rangle = \frac{c_s}{2 n_{0e}} \hat{\gamma} k_\theta \rho_s \cdot R_e \sum_k \left\langle \hat{n}_z \cdot \left(-i\tilde{\phi}\right)^* \right\rangle$$

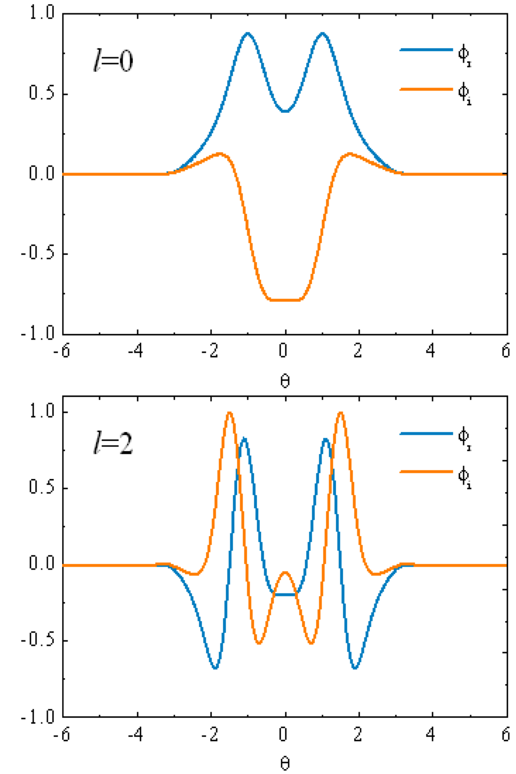
Multiple Eigenfunctions

Nucl. Fusion **57** 046019

Typical eigenfunctions of ITG mode



Typical eigenfunctions of TEM



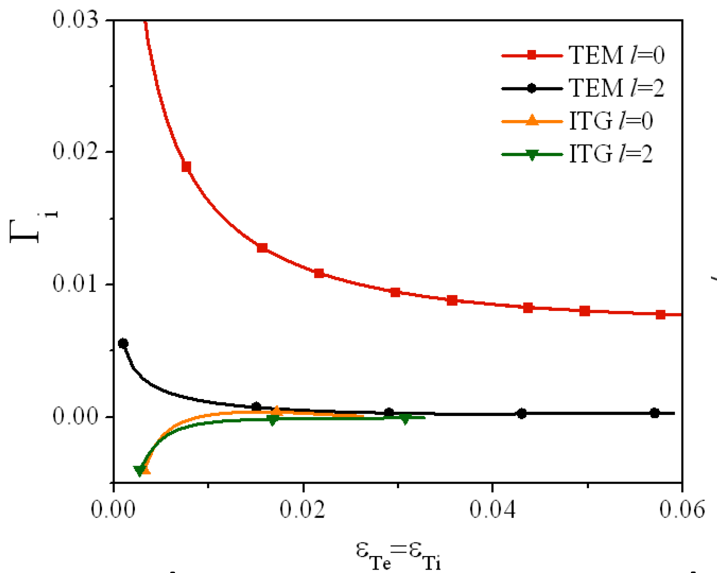
- ✓ At the steep gradients region, multiple eigenfunctions of TEM and ITG modes can be found.
- ✓ TEM has a more extended mode structures in ballooning space.

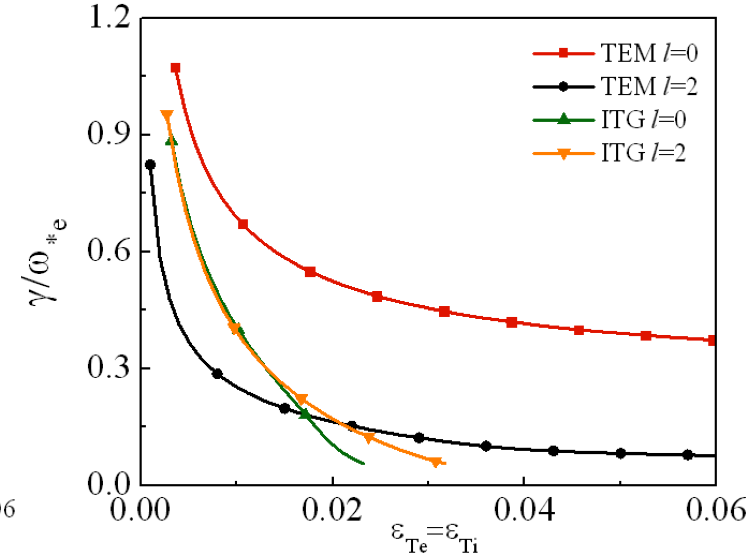
Different Temperature Gradient Effects for ITG and TEM

✓ Suppose: $\varepsilon_{Ti} = \varepsilon_{Te}$

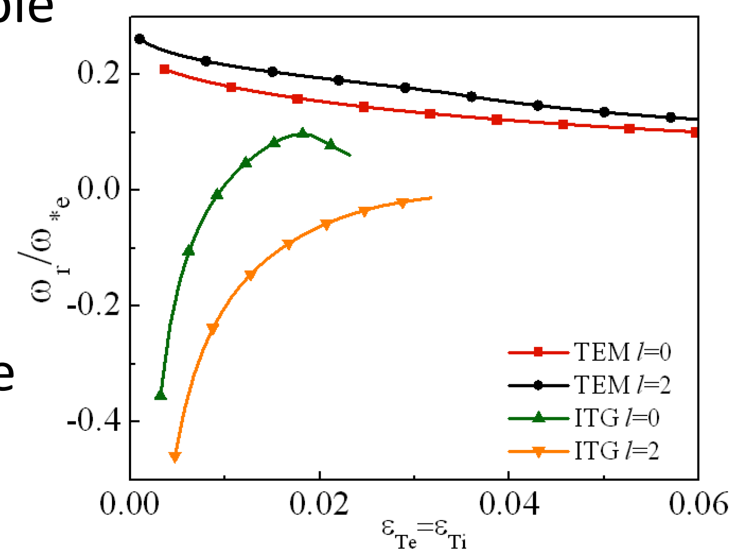
✓ $\varepsilon_{ni} = \varepsilon_{nei} = 0.0485$

✓ Other parameters are the same as the typical parameters.



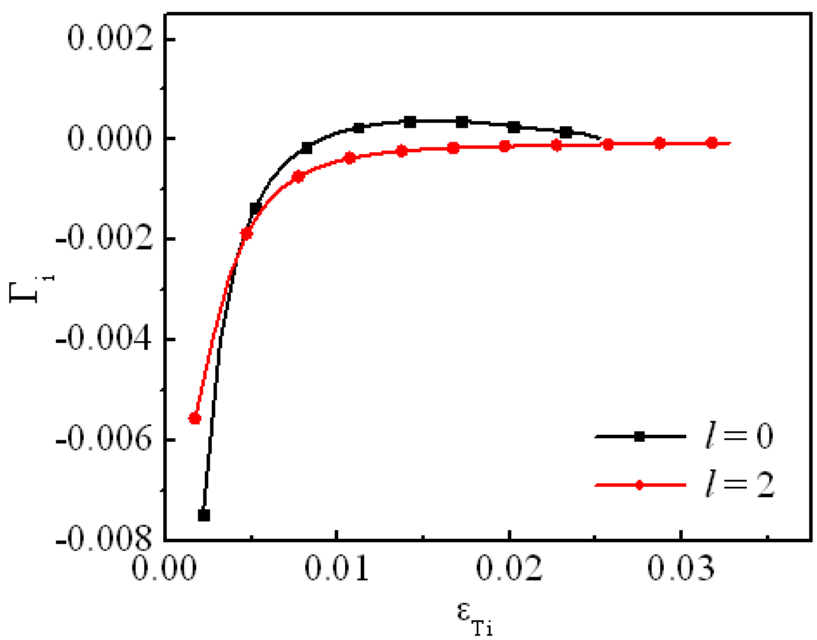


- Growth rate of ITG modes are more comparable than the TEMs.
- TEM's unstable region is larger than the ITG modes. This is agree with the experiment.
- Ion flux of the TEMs increase with the increase of the temperature gradient, but opposite for the ITG modes.

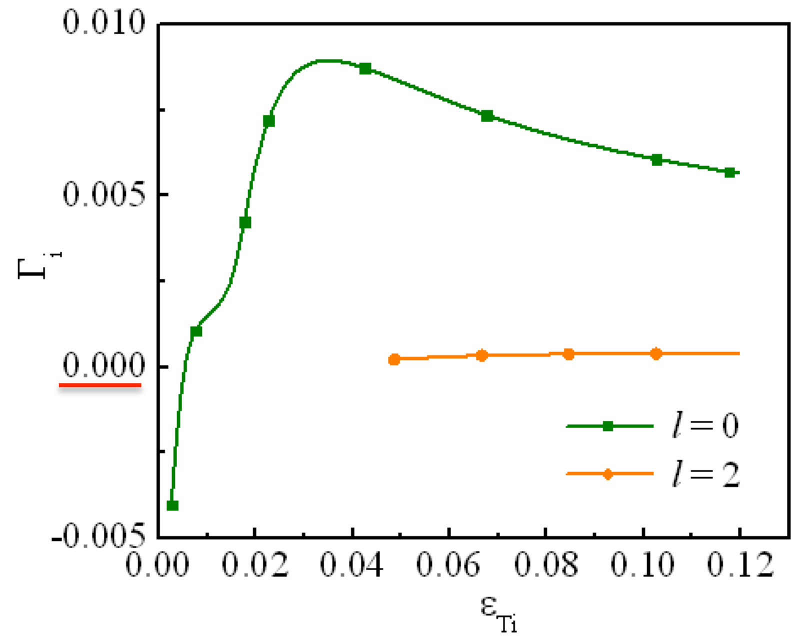


Ion Temperature Gradient Effect for ITG and TEM

Ion flux of the ITG modes



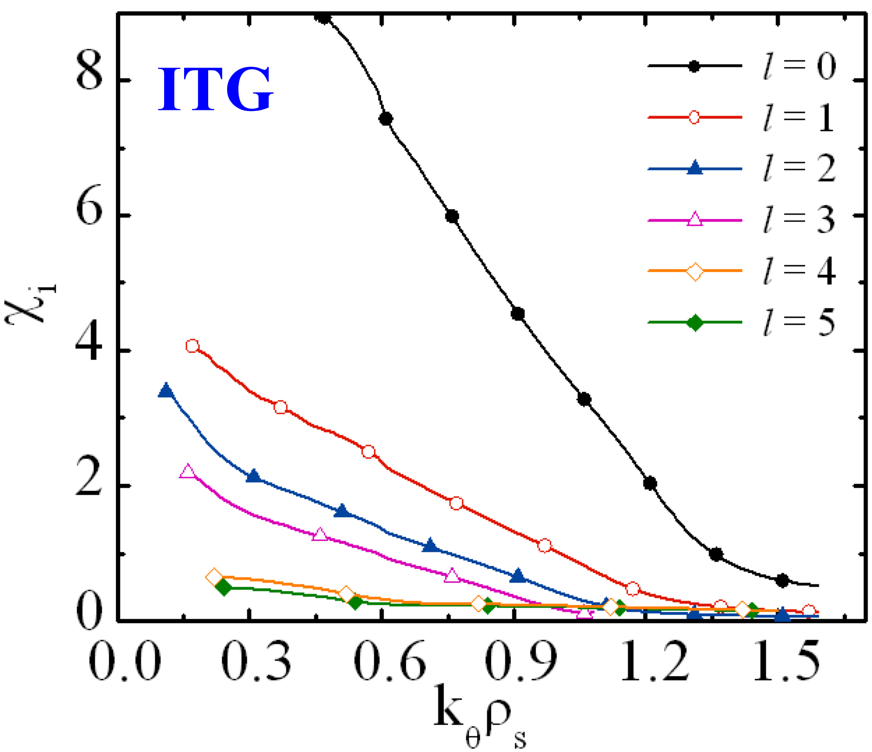
Ion flux of the TE-ITG modes



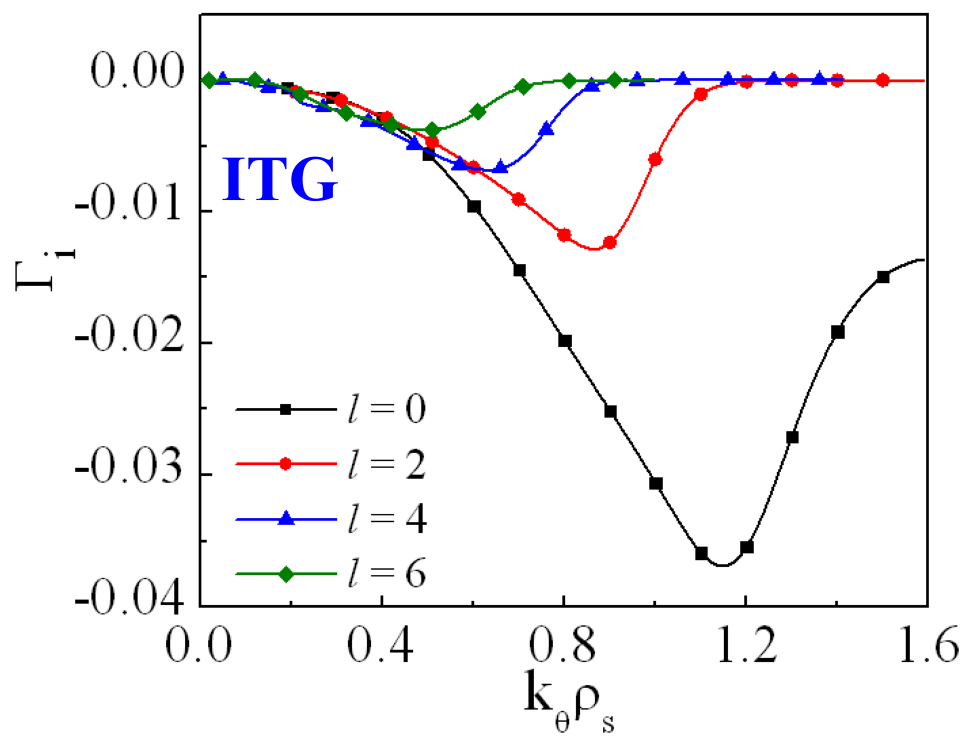
- ✓ Suppose: $\boldsymbol{\varepsilon_{ni} = \varepsilon_{ne}}$. Other parameters are the same as the typical TB's parameters.
- ✓ Ion flux of the ITG modes are comparable, but not for the TE-ITG modes.
- ✓ Steep $\boldsymbol{\varepsilon_{Ti}}$ enlarge the ion inwardly transport of the ITG mode, but decrease the ion outwardly transport of TEM.
- ✓ When the ion temperature gradient is steep enough, ion transport of the TE-ITG modes changed into outwardly

Different Turbulent Transport Estimations

Quasi-linear mixing length



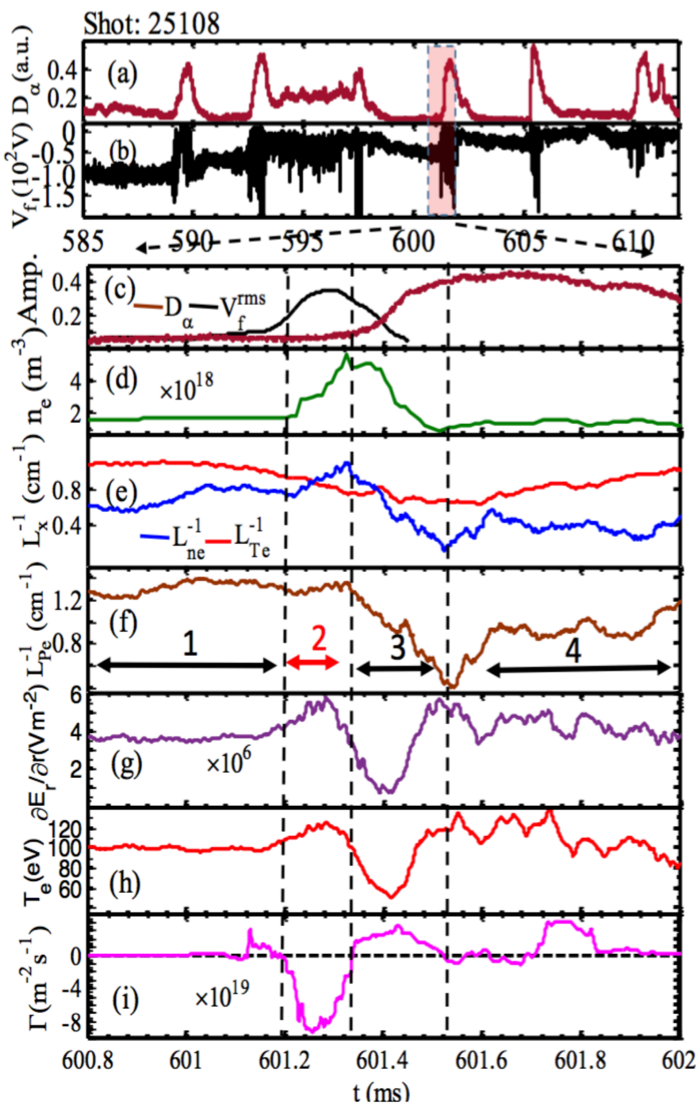
Quasi-linear particle flux



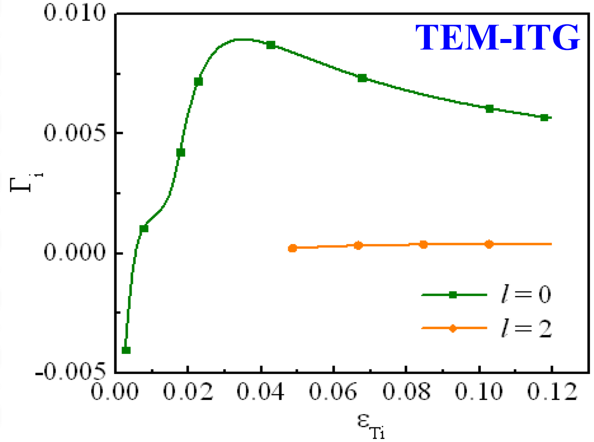
- ✓ Mixing length estimation of the diffusion coefficient decrease with $k_\theta\rho_s$.
- ✓ Particle flux estimations of the transport are inwardly and first increase with $k_\theta\rho_s$ increasing and then decrease with $k_\theta\rho_s$.

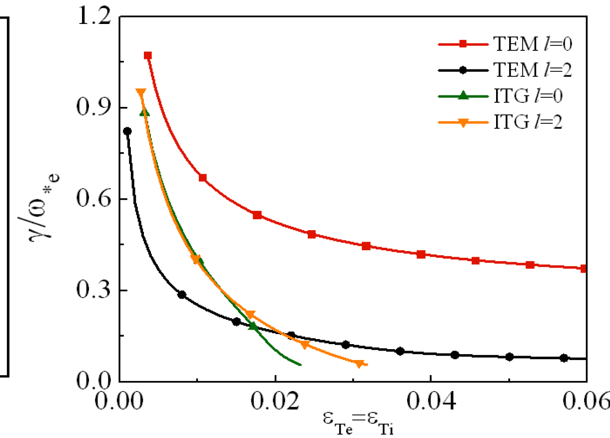
Simulations Agree with the Experimental Results

Experimental results from HL-2A



HD7 simulation results based on the typical TB's parameters of HL-2A

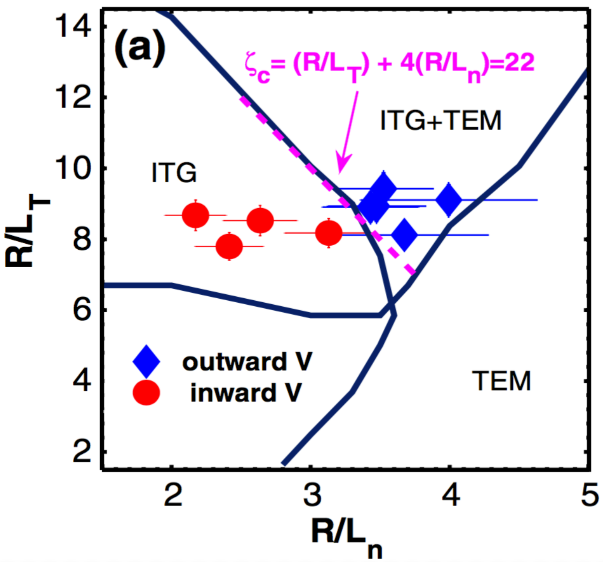




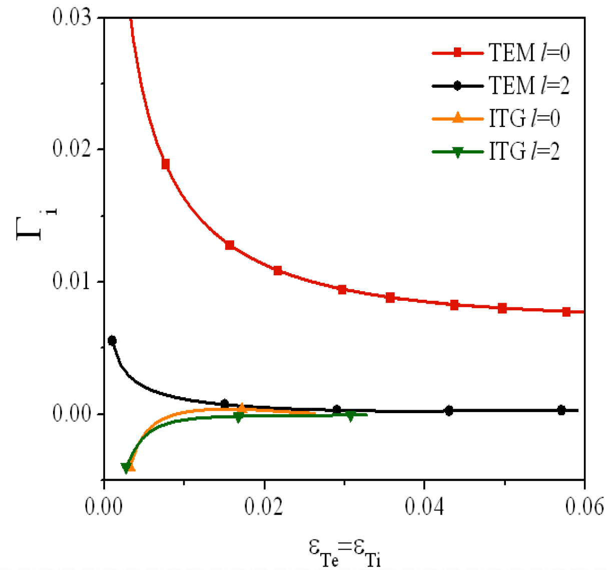
- ✓ Under the typical TB's parameter, when ε_{Ti} is steep enough, ion flux of the TEM-ITG is inwardly.
- ✓ Under the typical TB's parameter, the dominant instabilities is TEM and the real frequency is in electron diamagnetic drift direction.
- ✓ The typical TB's parameters $\eta_i = 0.80,\ k_\theta \rho_s = 0.6,\ q = 3,$ $\hat{s} = 1.6,\ \eta_e = 0.80,\ \varepsilon_n = 0.048,$ $\tau = 1.25,\ \varepsilon = 0.23$

Simulations Agree with the Experimental Results

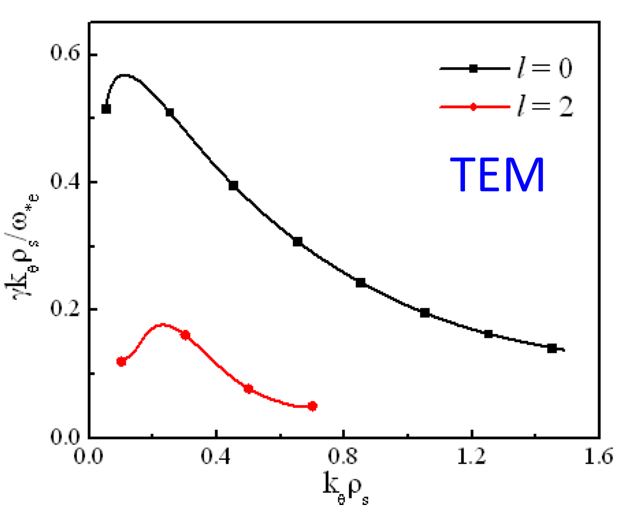
Tore Supra experimental results

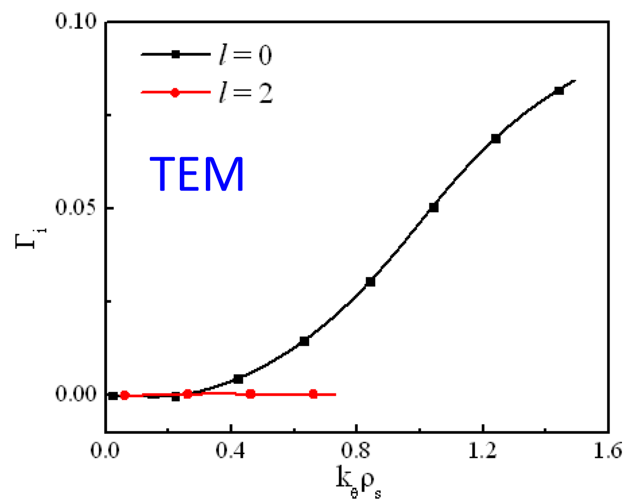


HD7 simulation results



- Simulation results that the ion flux of the ITG are inwardly and that of ITG +TEM are outwardly. This is similar to the result from results from Tore Supra tokamak





- TEM with high mode-number *l* seems not very important.

Thank you very much!