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Global structure of ITG turbulence-zonal mode system in tokamak plasmas

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Outline
- Zonal flows and GAM
- Nonlinear interaction between ITG turbulence and ZFs
- ZF behaviour in reversed shear plasmas

Introduction

- For high performance plasmas, suppression of anomalous transport or formation of transport barrier is essential.
- It is considered that drift wave turbulence such as ion temperature gradient (ITG) driven turbulence and zonal flow generated from the turbulence play an important role in the anomalous transport and the formation of transport barriers.
- Recent local simulations (Hallatschek 2001, Scott 2003) and experiments in TEXT (Schoch), DIII-D (McKee 2003), ASDEX-U (Conway 2004),JFT-2M (Ido 2004) and JIPPT-IIU (Hamada 2004) showed the ZFs near edge oscillate.
- The oscillation of ZFs is geodesic acoustic mode (GAM) (Winsor 1968).
- Time varying ZFs are less effective in suppressing turbulence compared to the stationary ZFs (Hahm 1999).
- It is important in understanding the formation of transport barrier and controlling the turbulent transport to investigate global variation of the zonal flow behaviour in tokamak plasmas.

Two kinds of ZF in toroidal plasmas (stationary ZF and GAM)

Reynolds / Maxwell

ZF eq.

$$\frac{\partial \langle v_E \rangle}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r} r^2 \langle \tilde{v}_{Er} \tilde{v}_{E\theta} \rangle + \frac{\beta}{n_{eq}} \frac{1}{r^2} \frac{\partial}{\partial r} r^2 \langle \tilde{B}_r \tilde{B}_\theta \rangle - \frac{2}{n_{eq}} \frac{a}{R} \langle p \sin\theta \rangle$$

(m,n)=(1,0) pressure eq.

$$\frac{\partial}{\partial t}\langle p \sin\theta \rangle = -\langle [\tilde{\phi}, \tilde{p}] \sin\theta \rangle + (\Gamma + \tau)\frac{a}{qR} \langle v_\parallel \cos\theta \rangle + (\Gamma + \tau)\frac{a}{R} p_{eq} \langle v_E \rangle$$

(m,n)=(1,0) parallel ion velocity eq.

$$\frac{\partial}{\partial t}\langle v_\parallel \cos\theta \rangle = -\langle [\tilde{\phi}, \tilde{v}_\parallel] \cos\theta \rangle - \frac{1}{n_{eq}} \frac{a}{qR} \langle p \sin\theta \rangle$$

Stationary ZFs $(\partial_t = 0)$

$$\langle v_E \rangle = -\frac{1}{p_{eq} q} \langle v_\parallel \cos\theta \rangle$$

$$\langle p \sin\theta \rangle = 0$$

GAM $(q \gg 1)$

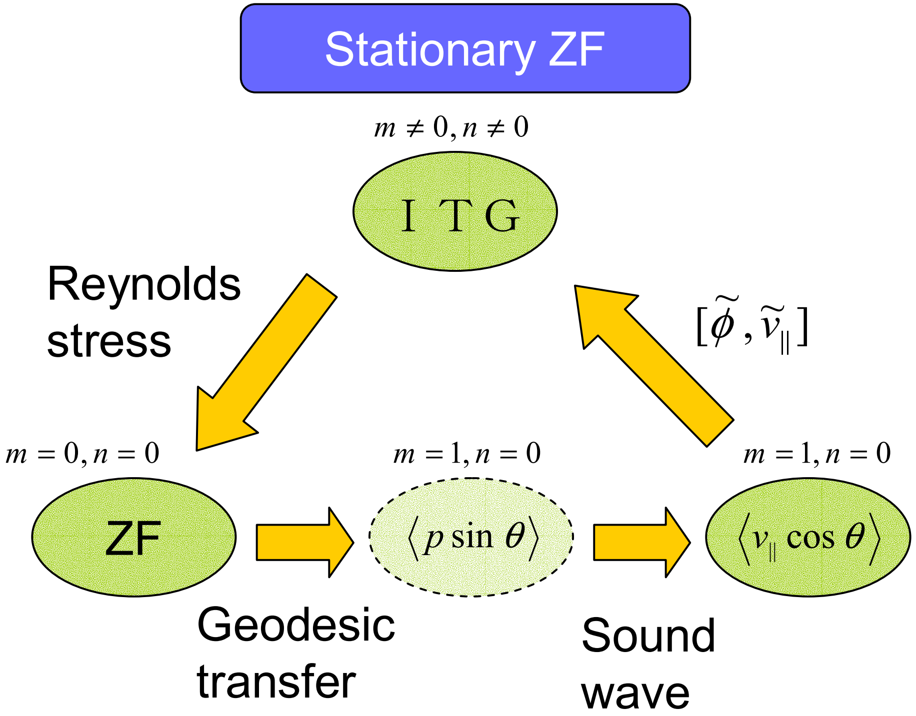
$$\frac{\partial^2 \langle v_E \rangle}{\partial t^2} = -2(\Gamma + \tau) T_{eq} \left(\frac{a}{R}\right)^2 \langle v_E \rangle$$

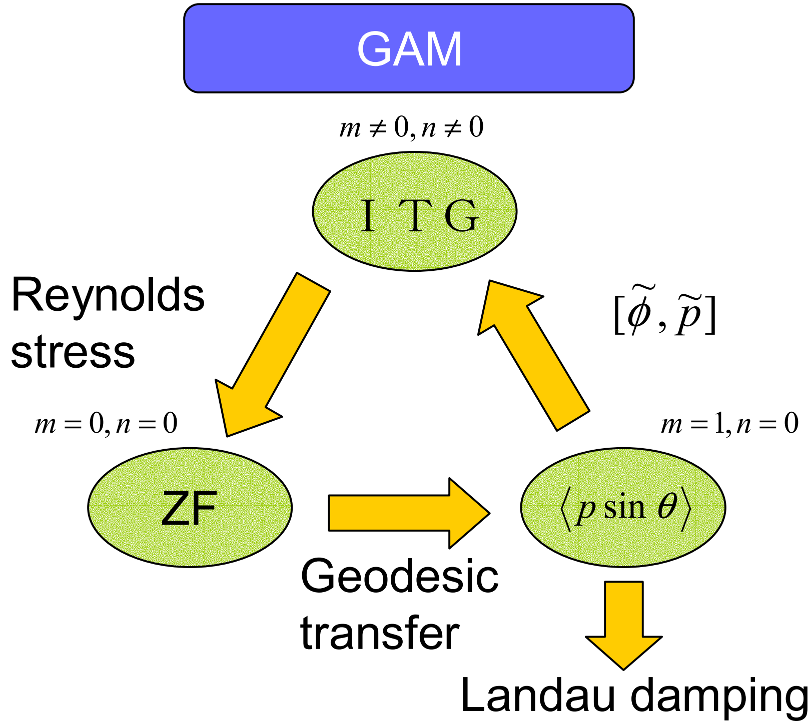
$$\Rightarrow \hat{\omega}_{\mathrm{GAM}} = \sqrt{2(\Gamma + \tau) T_{eq}} \frac{a}{R}$$

GAM is oscillation between zonal flow $\langle v_E \rangle = \frac{\partial \phi_0}{\partial r}$ and (m, n) = (1,0) pressure perturbation $\langle p \sin\theta \rangle$

(1,0) parallel sound wave frequency $\hat{\omega}_{\mathrm{sound}} = \sqrt{(\Gamma + \tau) T_{eq}} \frac{a}{qR}$

Energy loop between ZFs and ITG turbulence in quasi steady state





The stationary ZFs saturate due to the saturation of the parallel flows by the turbulent viscosity. (Hallatschek 2004)

The nonlinear transfer from poloidally asymmetric pressure perturbations to the ITG turbulence contributes to the saturation of the oscillatory zonal flows.

5-field Landau-fluid model

Continuity equation

$$\frac{1}{n_{eq}}\frac{dn}{dt} = \frac{a}{n_{eq}}\frac{dn_{eq}}{dr}\nabla_\theta\phi - \nabla_\parallel v_\parallel + \frac{\nabla_\parallel j}{n_{eq}} + \omega_d\left(\phi - \tau\frac{T_{eq}}{n_{eq}}n - T_e\right) + D_n\nabla_\perp^2 n$$

Vorticity equation

$$\frac{d}{dt}\nabla_\perp^2\phi = -T_{eq}\frac{L}{n_{eq}}\frac{dn_{eq}}{dr}(1+\eta_i)\nabla_\theta\nabla_\perp^2\phi + \frac{1}{n_{eq}}\nabla_\parallel j$$
$$-\omega_d\left(T_i + T_e + \frac{T_{eq}}{n_{eq}}(1+\tau)n\right) + D_U\nabla_\perp^r\phi$$

Equation of parallel motion for ion fluid

$$\frac{dv_\parallel}{dt} = -\nabla_\parallel T - (1+\tau)\frac{T_{eq}}{n_{eq}}\nabla_\parallel n - \beta T_{eq}\frac{L}{n_{eq}}\frac{dn_{eq}}{dr}(1+\eta_i+\tau)\nabla_\theta A_\parallel + D_v\nabla_\perp^2 v_\parallel$$

Equation of parallel motion for electron fluid

Electron Landau damping

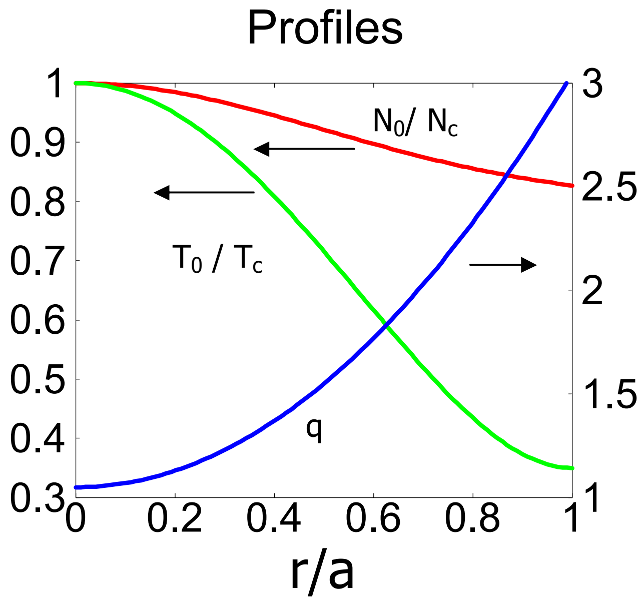
$$\beta\frac{\partial A_\parallel}{\partial t} = -\nabla_\parallel\phi + \tau\frac{T_{eq}}{n_{eq}}\nabla_\parallel n + \beta\tau T_{eq}\frac{L}{n_{eq}}\frac{dn_{eq}}{dr}\nabla_\theta A_\parallel + \boxed{\sqrt{\frac{\pi}{2}\tau\frac{m_e}{m_i}}|k_\parallel|\left(v_\parallel - \frac{j}{n_{eq}}\right)} - \eta j$$

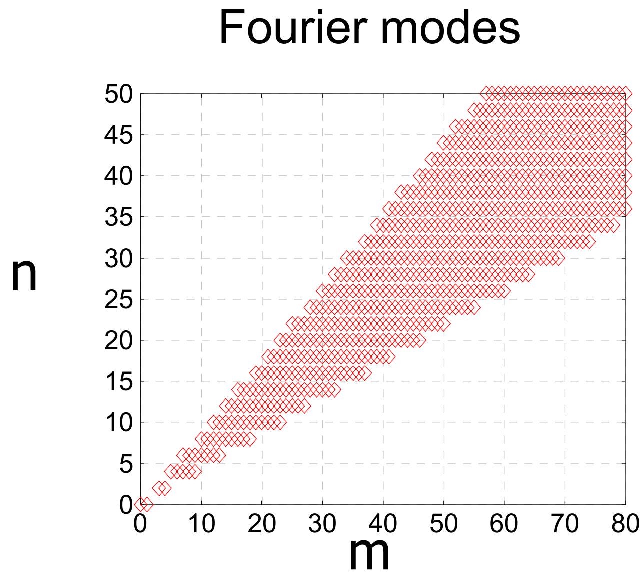
Ion temperature equation

$$\frac{dT}{dt} = T_{eq}\frac{a}{n_{eq}}\frac{dn_{eq}}{dr}\eta_i\nabla_\theta\phi - \frac{2}{3}T_{eq}\nabla_\parallel v_\parallel \boxed{- \frac{2}{3}\sqrt{\frac{8T_{eq}}{\pi}}|k_\parallel|T}$$
$$+T_{eq}\omega_d\left(\frac{2}{3}\phi + \frac{7}{3}T + \frac{2}{3}\frac{T_{eq}}{n_{eq}}n\right) + D_T\nabla_\perp^2 T$$

Ion Landau damping

Parameters





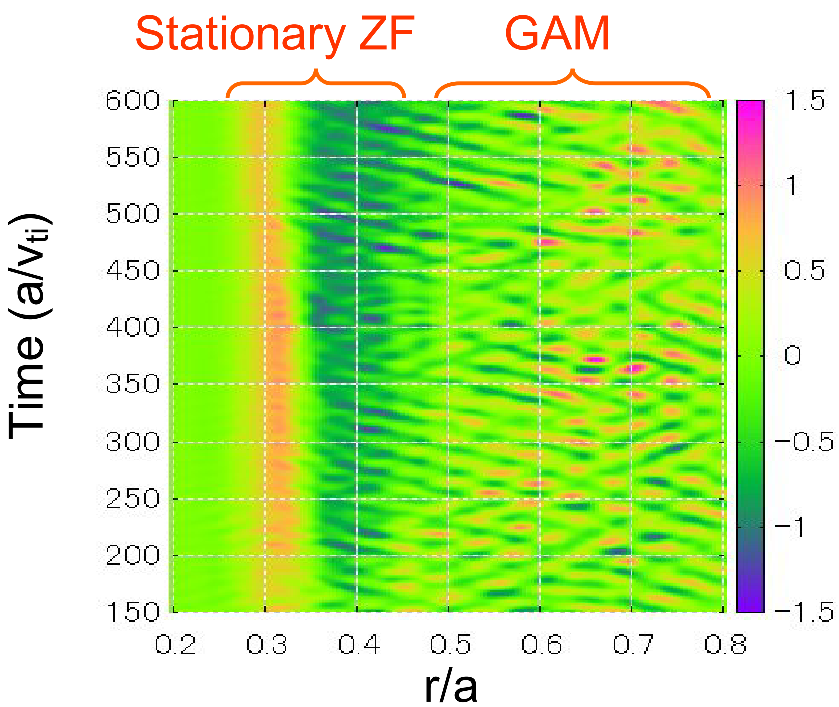
$R_0 / a = 4, \rho_i / a = 0.0125,$

$T_e / T_i = 1, \beta = 0.001$

Resonant modes in the region $0.2 < r/a < 0.8$
and nonresonant (0,0), (1,0) modes

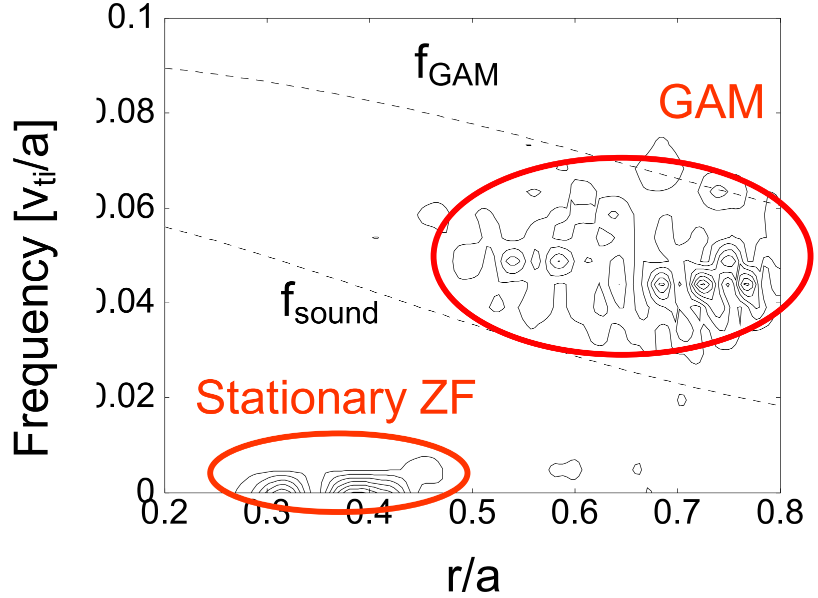
- Artificial dissipations are set to make small scale modes (m>50) linearly stable.

ZF behaviour depends on relation between f_{sound} and f_{ZF}



Low q region

The (1,0) pressure perturbations relax along the magnetic field, so that the ZFs are stationary.



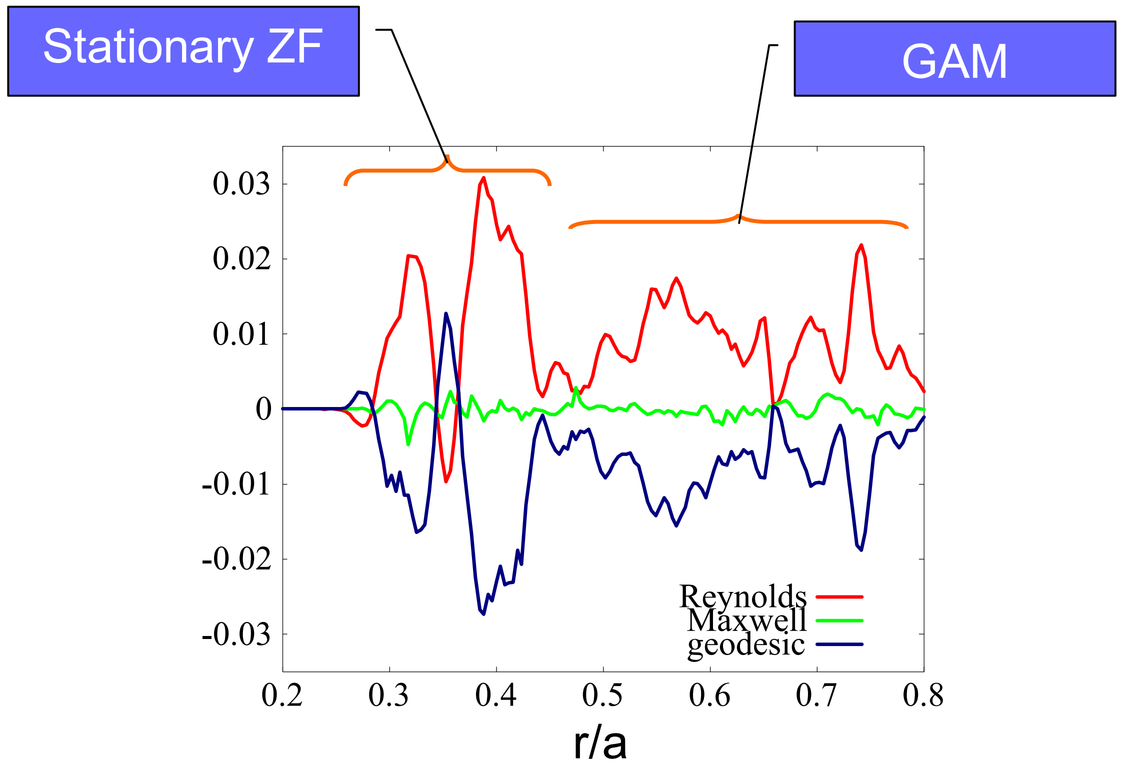
High q region

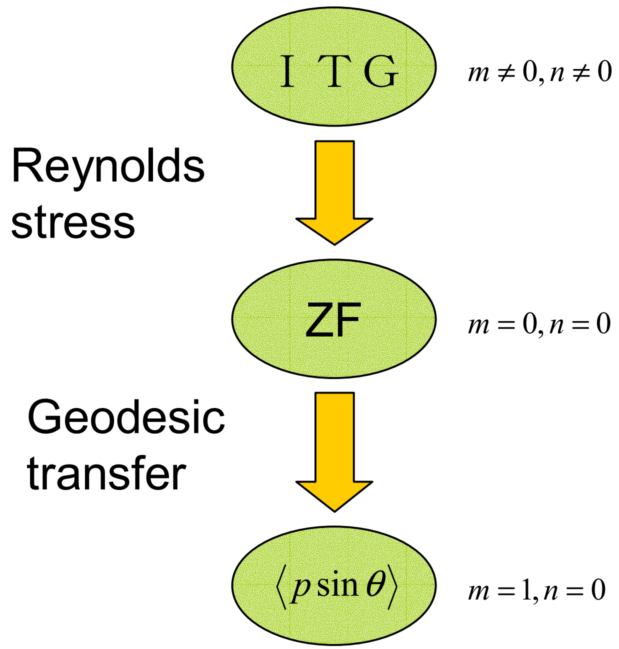
The ZFs oscillate with the (1,0) pressure perturbations.

ZFs are generated by Reynolds stress which balances with geodesic transfer

$$\frac{\partial}{\partial t}\frac{1}{2}\langle v_E\rangle^2 = -\langle \tilde{v}_r \tilde{\Omega}\rangle\langle v_E\rangle + \hat{\beta}\langle \tilde{B}_r \tilde{j}\rangle\langle v_E\rangle - 2\frac{a}{R_0}\langle p\sin\theta\rangle\langle v_E\rangle$$

Reynolds　　Maxwell　　Geodesic　transfer

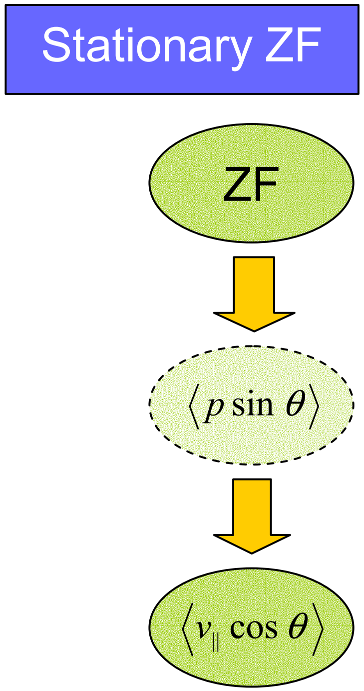


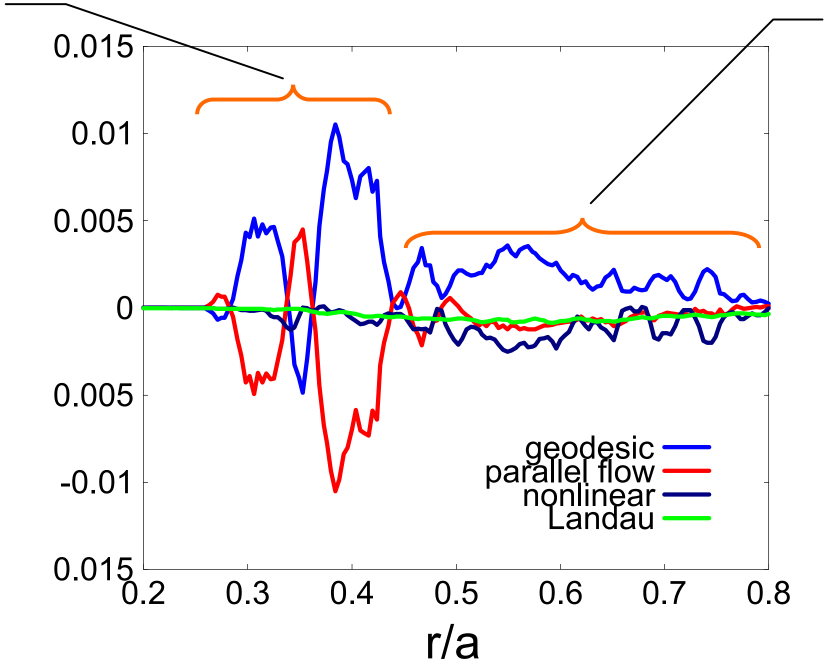


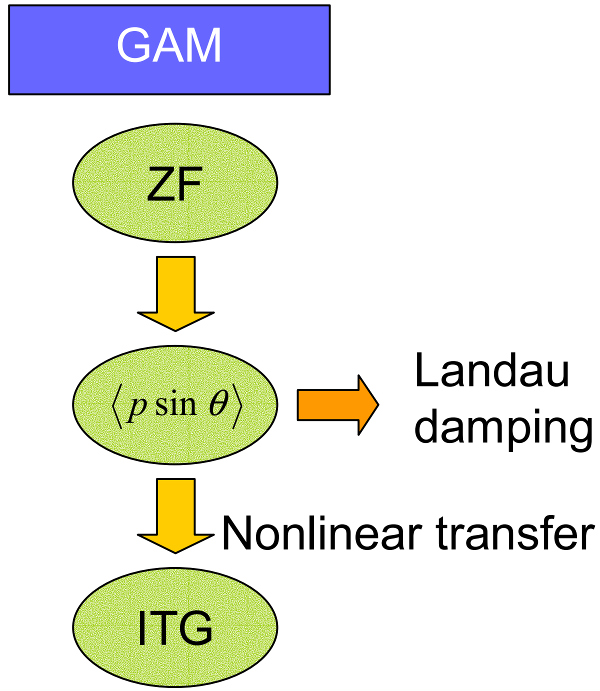
Nonlinear transfer contributes to saturation of GAMs

$$\frac{\partial}{\partial t}\langle p\sin\theta\rangle^2 = -\langle[\tilde{\phi},\tilde{p}]\sin\theta\rangle\langle p\sin\theta\rangle + (\Gamma+\tau)p_{eq}\frac{a}{qR}\langle v_\parallel\cos\theta\rangle\langle p\sin\theta\rangle - (\Gamma-1)\sqrt{\frac{8T_{eq}}{\pi}}\frac{a}{qR}\langle T_i\sin\theta\rangle\langle p\sin\theta\rangle + (\Gamma+\tau)p_{eq}\frac{a}{R}\langle v_E\rangle\langle p\sin\theta\rangle$$

Nonlinear transfer | Sound wave | Landau damping | Geodesic transfer





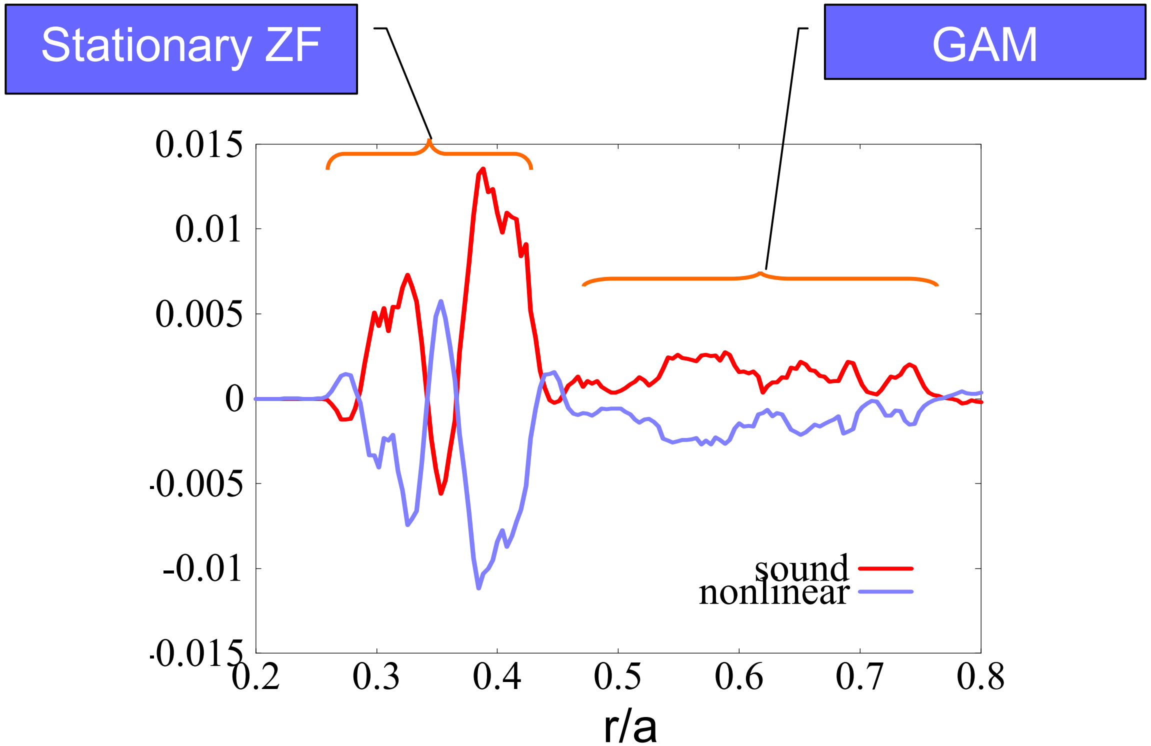


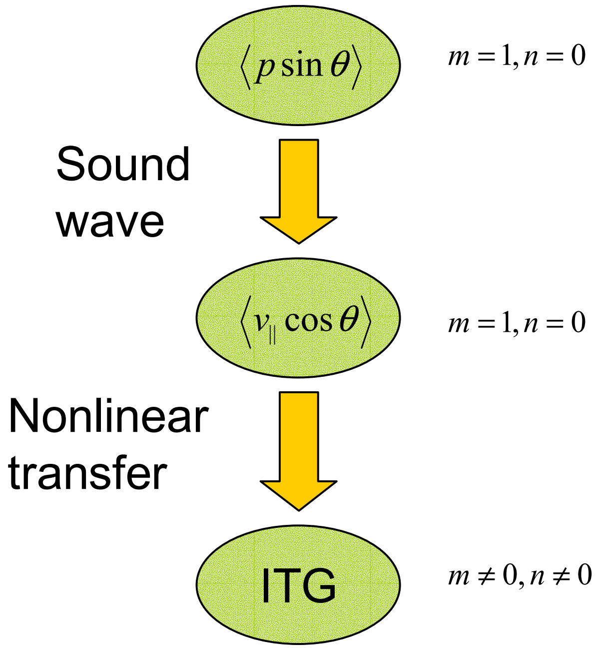
In the GAM region, the energy from ZFs is consumed by nonlinear transfer to the ITG turbulence as well as Landau damping, which is the same as the result of 4-field drift-Alfvén turbulence simulation. (Scott 2003)

Parallel flows saturate by nonlinear transfer to turbulence

$$\frac{\partial}{\partial t}\frac{1}{2}\left\langle v_{\parallel}\cos\theta\right\rangle^{2} = -\left\langle[\phi,\tilde{v}]\cos\theta\right\rangle\left\langle v_{\parallel}\cos\theta\right\rangle - \frac{1}{n_{eq}}\frac{a}{qR_{0}}\left\langle p\sin\theta\right\rangle\left\langle v_{\parallel}\cos\theta\right\rangle$$

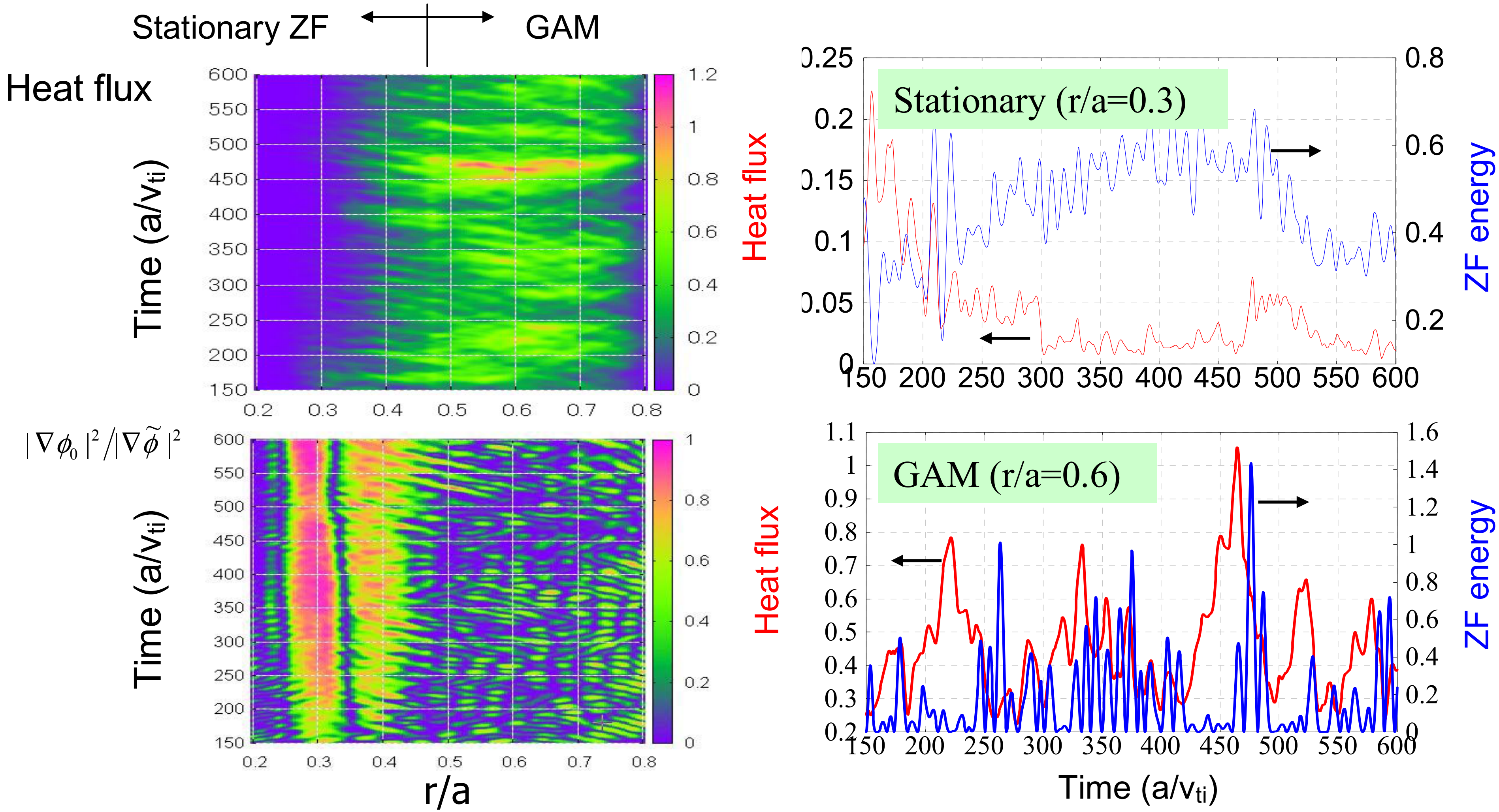
Nonlinear — Sound wave





The stationary zonal flows are saturated by the nonlinear transfer of parallel flow energy to the turbulence. (Hallatschek 2004)

Stationary ZFs suppress turbulent transport effectively

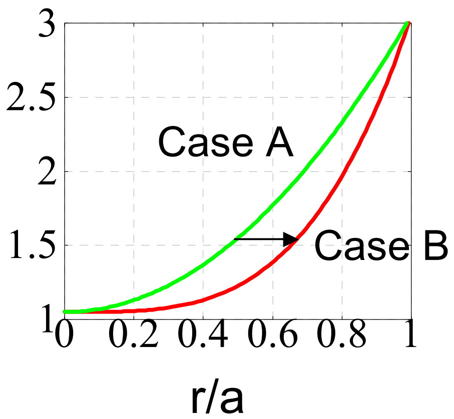


Transport reduction by control of zonal flow behaviour

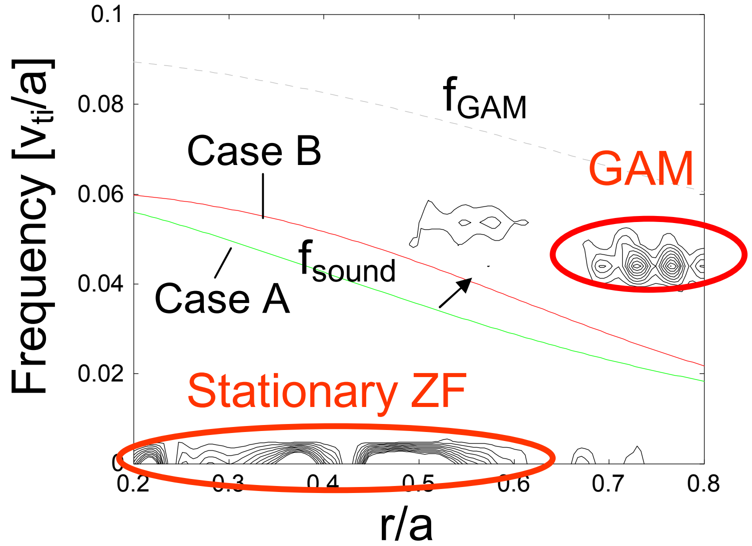
q-profile

Case A : $q = 1.05 + 2(r/a)^2$

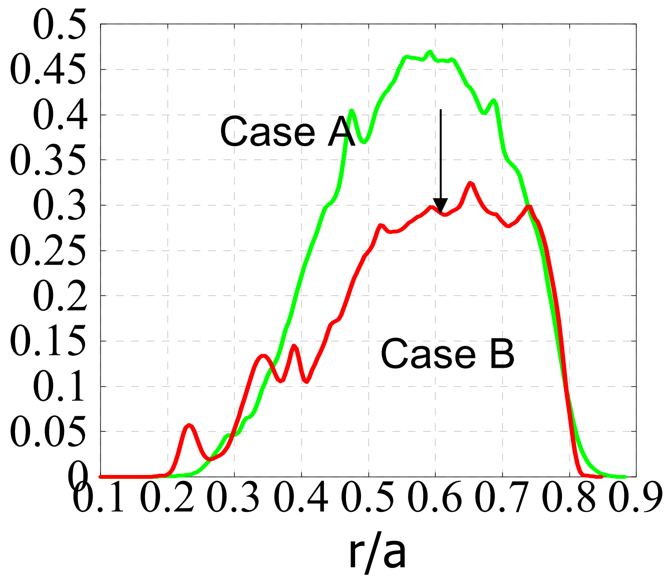
Case B : $q = 1.05 + 2(r/a)^{3.5}$



Shift of f_{sound} to higher frequency expands the stationary ZF region.

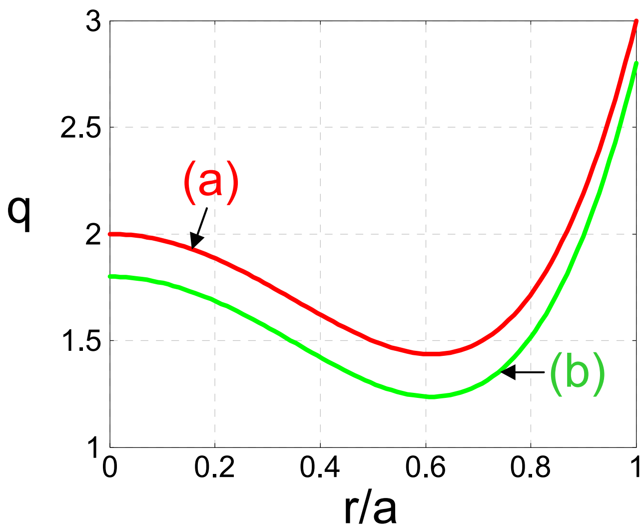


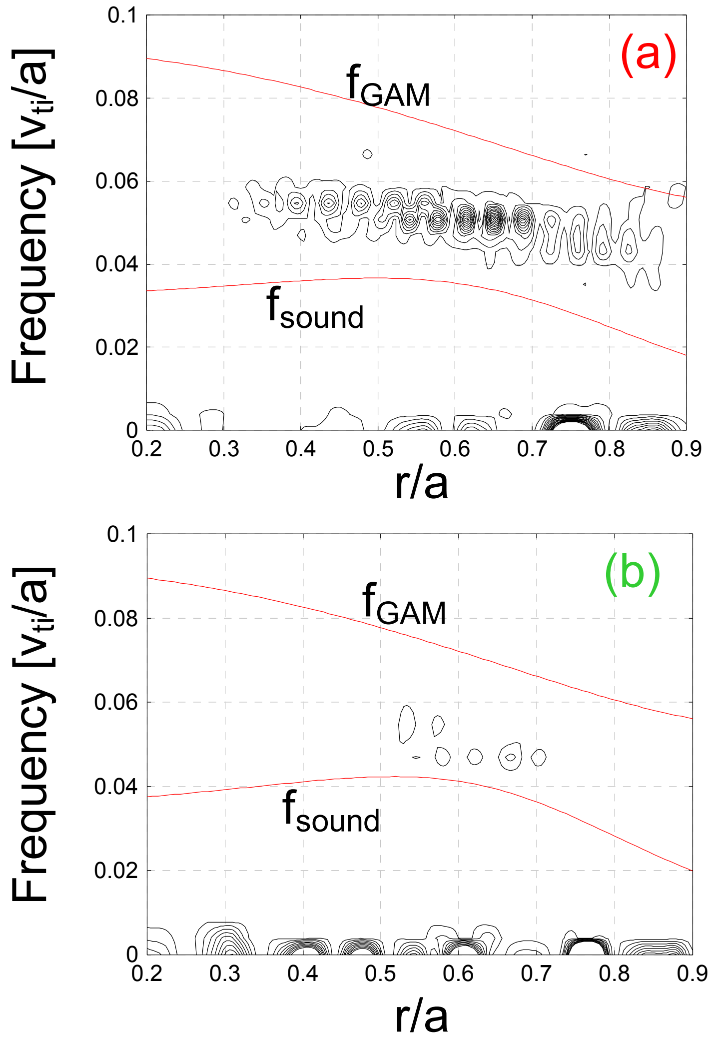
Time averaged heat flux



The change of q-profile leads to the expansion of the stationary ZF region by which the turbulent transport in Case B is reduced compared to Case A.

ZF behaviour in RS plasmas

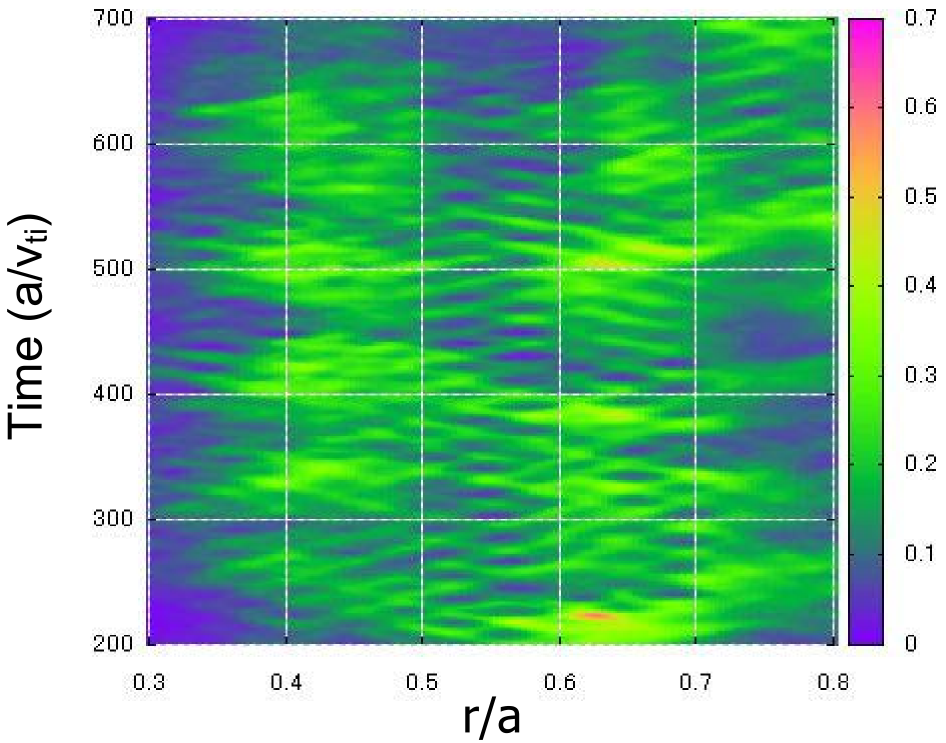




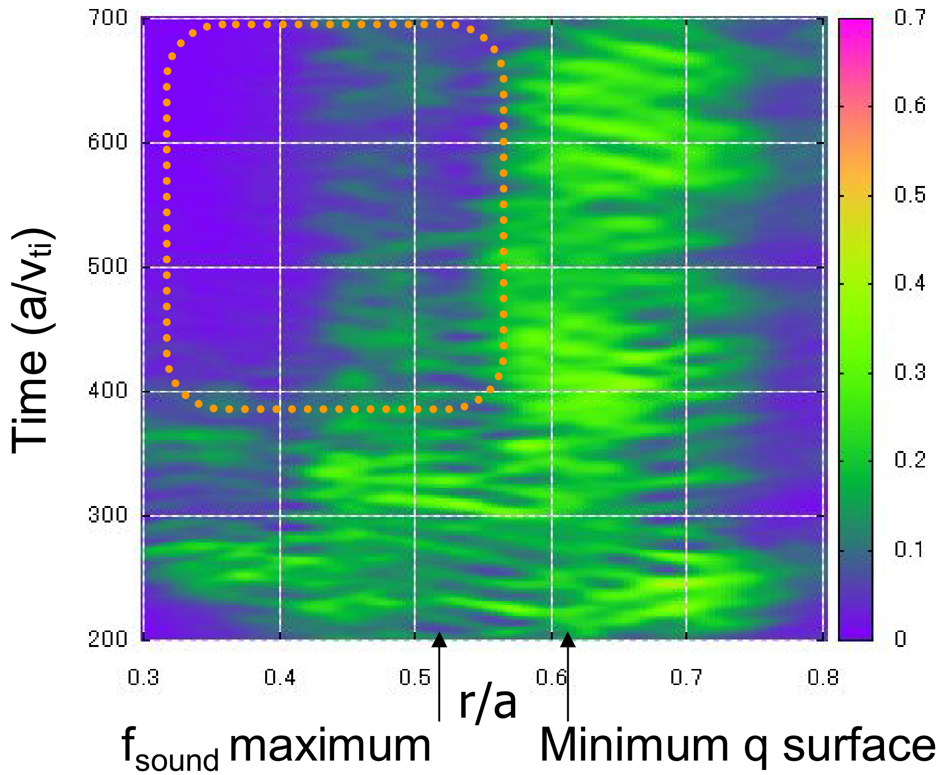
- The oscillatory ZFs are dominant in case (a).
- Increase of f_{sound} by decreasing q makes the stationary ZFs dominant.

Effect on heat transport

(a) $q = 2 - 3(r/a)^2 + 4(r/a)^4$



(b) $q = 1.8 - 3(r/a)^2 + 4(r/a)^4$



- In the higher q case (a) heat transport is high in a broad region because the oscillatory zonal flows are dominant.
- In the lower q case heat transport is suppressed by stationary zonal flows, but the heat flux on the minimum q surface (r=0.61) is still high.

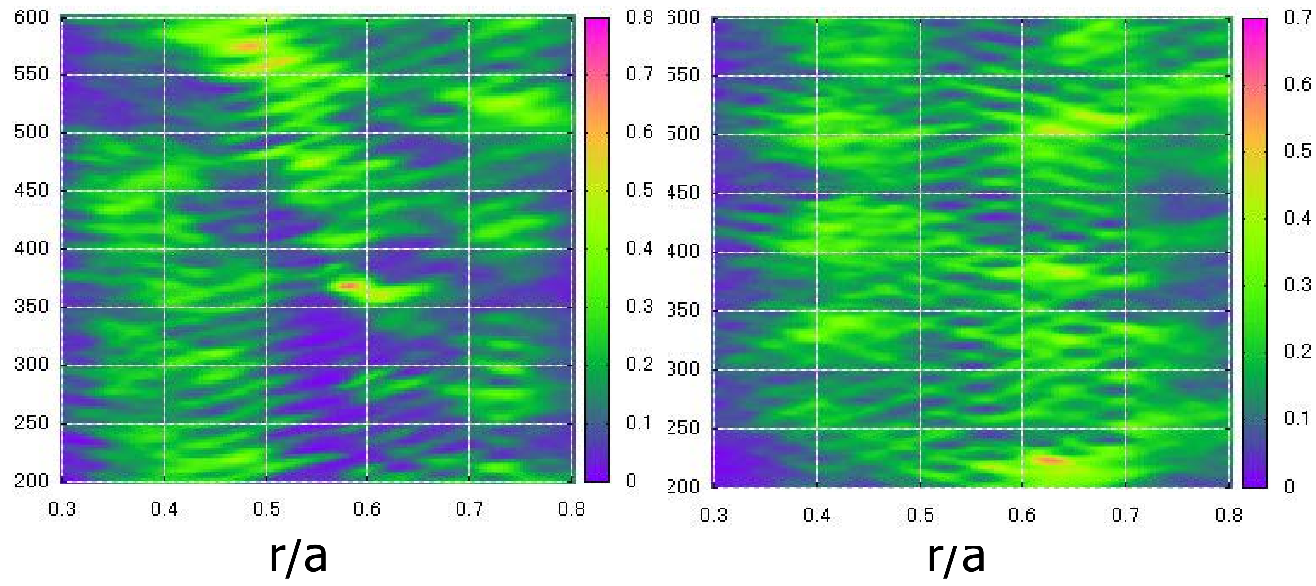
Summary and conclusions

- Two types zonal flows, stationary and oscillatory mode, are possible in tokamak plasmas with a realistic q profile.
  - In the low q region the stationary zonal flows are dominant. They suppress the turbulence effectively and become dominant over the turbulence.
  - In the high q region the zonal flows oscillate with the (1,0) pressure perturbations (GAM). The oscillatory zonal flows are less effective in suppressing the turbulence.
- The energy flow between the zonal flows and the ITG turbulence changes with the zonal flow type.
  - Stationary ZFs : ITG→ZF→ (〈psin θ〉) → 〈vcos θ〉 →ITG
  - Oscillatory ZFs : ITG→ZF→ 〈psin θ〉 →ITG
- The turbulent transport can be controlled through the control of the zonal flow behaviour by the q profile.

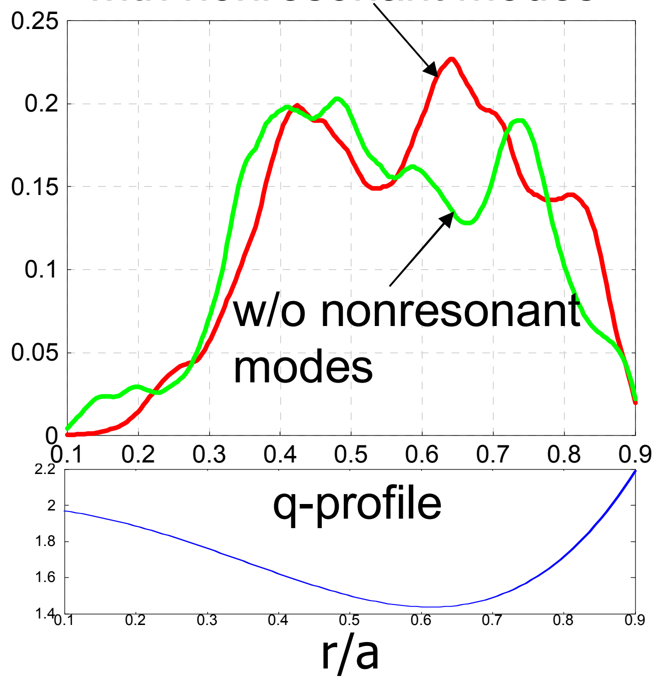
Effect of non-resonant modes

Temporal evolution of heat flux

without nonresonant modes / with nonresonant modes



Time averaged heat flux

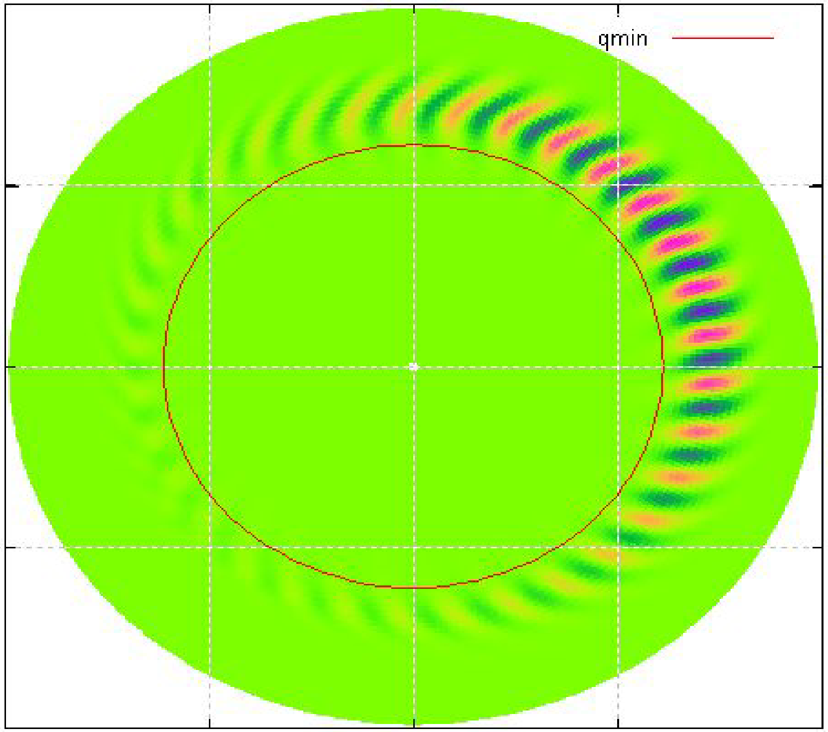


- Small heat flux region appears around the q_{min} surface in the case without nonresonant modes.
- No small heat flux region exists around the q_{min} surface when nonresonant modes are included in calculation.

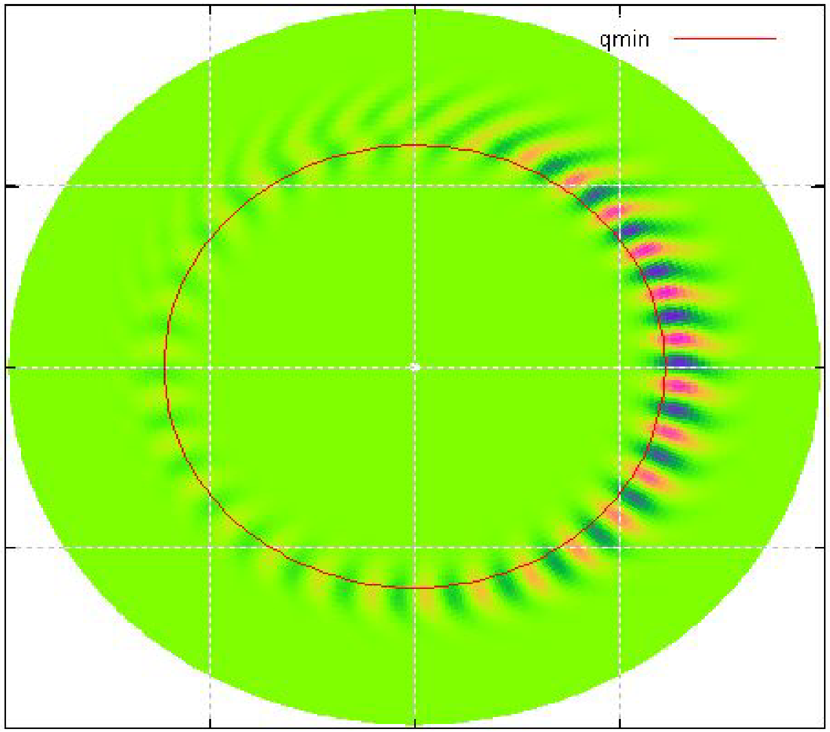
(The calculations were done in the electrostatic and adiabatic electron limit.)

Effect of nonresonant modes on linear structure

without nonresonant modes



with nonresonant modes



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