Gyrokinetic simulation of helical plasmas with field-line-label dependence

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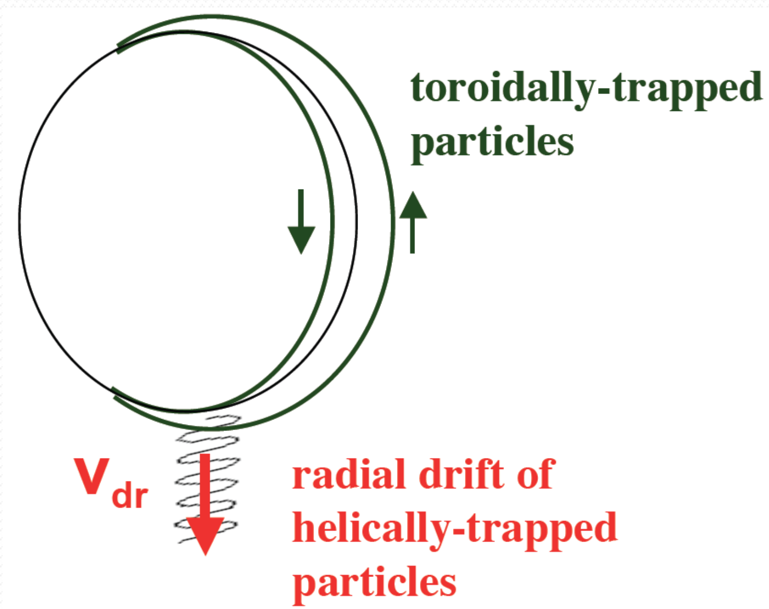
Outline

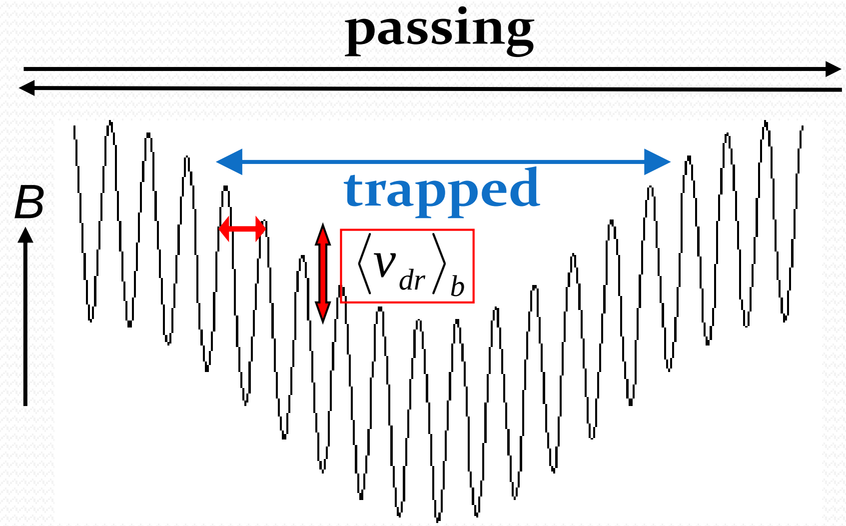
- Introduction
- Zonal-flow response in tokamak and helical systems with no E_r (E_r : equilibrium-scale radial electric field)
- Zonal flow response in helical systems with E_r
  - Radial wavenumber dependence of ZF response
  - Mach number dependence of ZF response
- ITG mode simulations for helical systems with E_r
- Summary

Zonal flow response in helical configurations

Effect of Helical Field on Zonal Flow

$$B = B_0\left[1 - \varepsilon_t \cos\theta - \varepsilon_l \cos(L\theta - M\zeta)\right]$$



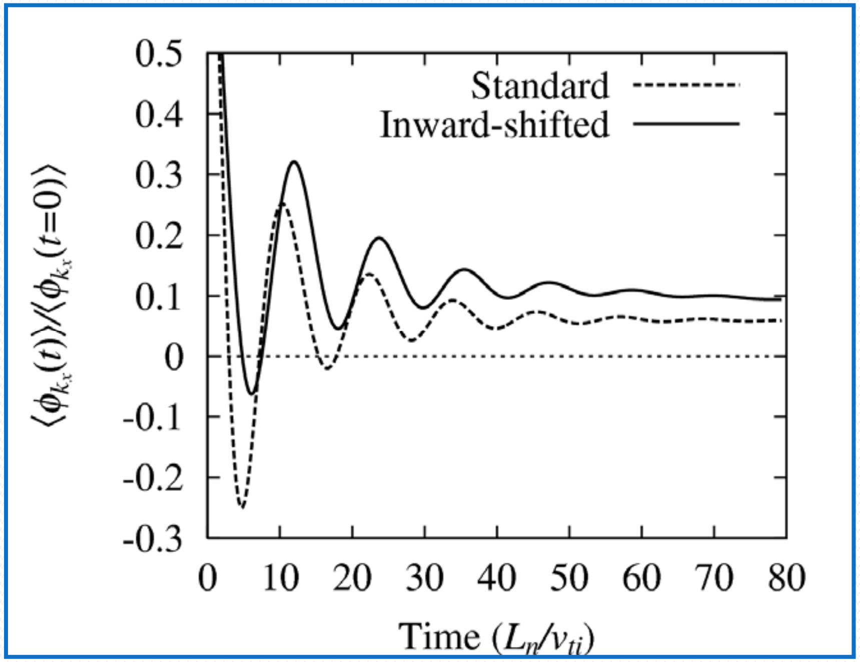


Classification of particle orbits in helical system

- Radial drift motion of helical-ripple-trapped particles leads to additional shielding effect of zonal flow.

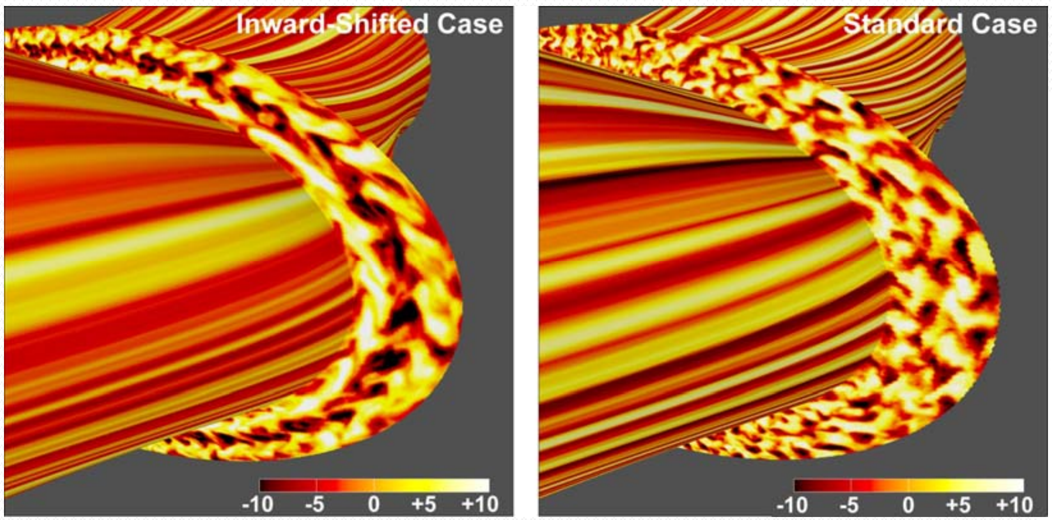
Zonal-Flow Enhancement in LHD Configuration

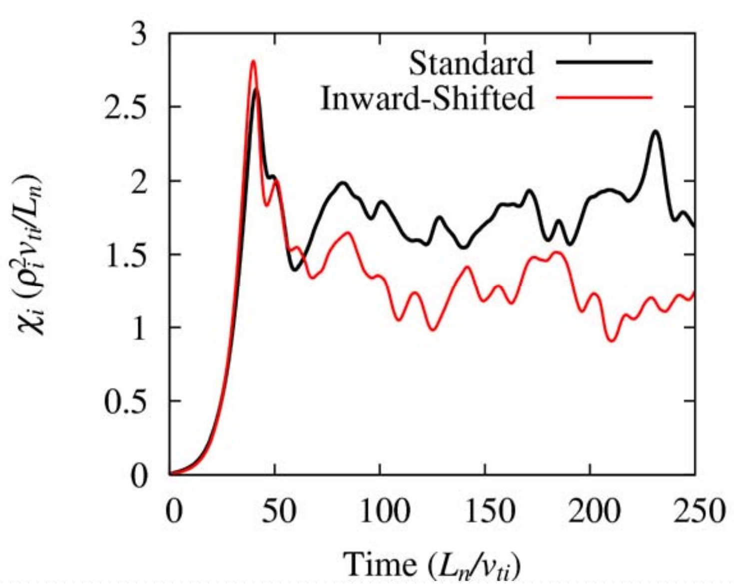
- Reduction of helical-ripple-trapped particle's drift improving the neoclassical transport also enhances the zonal-flow response with small shielding due to helical-ripple trapped particles.
- Higher ZF response is found for the inward-shifted LHD configuration.



Ferrando, Sugama & Watanabe, PoP 2007
Watanabe, Sugama & Ferrando, PRL 2008

Stronger zonal flows generated in inward-shifted configuration lower the ITG turbulent transport

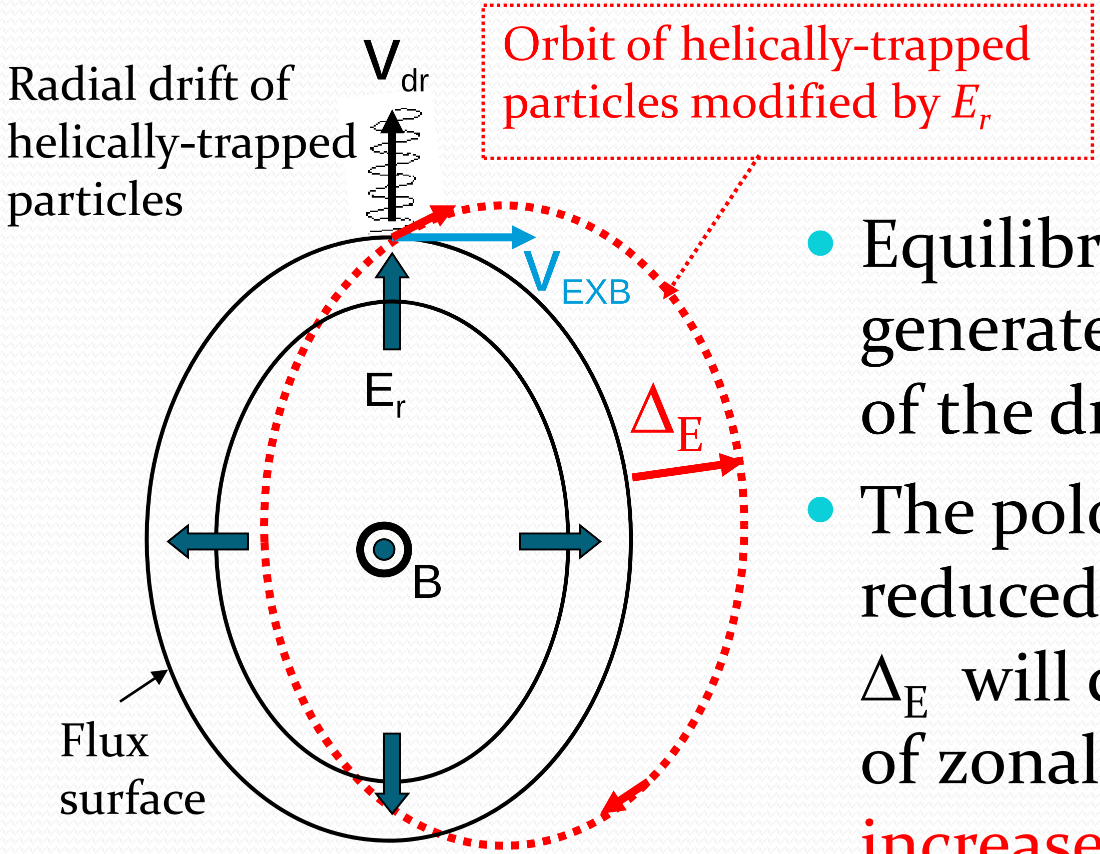




GKV simulation results for the I.-S. and Standard cases
(Watanabe, Sugama, & Ferrando., PRL 2008)

Zonal flow response in helical systems with E_r

Effects of Equilibrium-Scale E_r on Zonal-Flow Response



- Equilibrium-scale E_r field generates an *E*x*B* component of the drift velocity.
- The poloidal *E*x*B* rotation with reduced radial displacement Δ_E will decrease the shielding of zonal-flow potential and increase its response !

(Mynick & Boozer, PoP 2007)

Zonal Flow Responses

- Zonal flow response in tokamak (Rosenbluth-Hinton)

$$K \equiv \frac{\langle \phi_{k_x}(t=\infty) \rangle}{\langle \phi_{k_x}(t=0) \rangle} = \frac{1}{1+G} \approx \frac{1}{1+1.6q^2/\varepsilon^{1/2}}$$

- In case with no radial electric field (E_r=0)

$$\mathcal{K}_L(t) \equiv \frac{1-(2/\pi)\langle (2\epsilon_H)^{1/2}\{1-g_{i1}(t,\theta)\}\rangle}{1+G+\mathcal{E}(t)/\left(n_0\langle k_\perp^2 a_i^2\rangle\right)}$$

- Long-time response of zonal flow in case with E_r

$$\phi(t) = \frac{\phi(0)}{1+G_p+G_t+M_p^{-2}(G_{ht}+G_h)(1+T_e/T_i)} \qquad M_p = \left|\omega_\theta \frac{R_0 q}{v_{ti}}\right|, \quad \omega_\theta = -\frac{cE_r}{r_0 B_0}$$

Sugama, Watanabe & Ferrando, PFR 2008; Sugama & Watanabe, PoP 2009

GK Equation for ZFs with E_r

- Field-line label α dependence of $|B|$

$$B = B_0\left[1 - \varepsilon_t(r)\cos\left(\alpha + \iota\zeta/2\pi\right) - \sum_l \varepsilon_l(r)\cos\left(l\alpha + (\iota l/2\pi - M\zeta)\right)\right]$$

- Gyrokinetic equation for zonal flows with E_r

$$\left[\frac{\partial}{\partial t} + v_\parallel \hat{\mathbf{b}}\cdot\nabla + i\mathbf{k}_r\cdot\mathbf{v}_d - \mu\left(\hat{\mathbf{b}}\cdot\nabla\Omega\right)\frac{\partial}{\partial v_\parallel} + \omega_\theta\frac{\partial}{\partial\alpha}\right]\delta f = -i\mathbf{k}_r\cdot\mathbf{v}_d\frac{e\langle\psi\rangle}{T_i}F_M$$

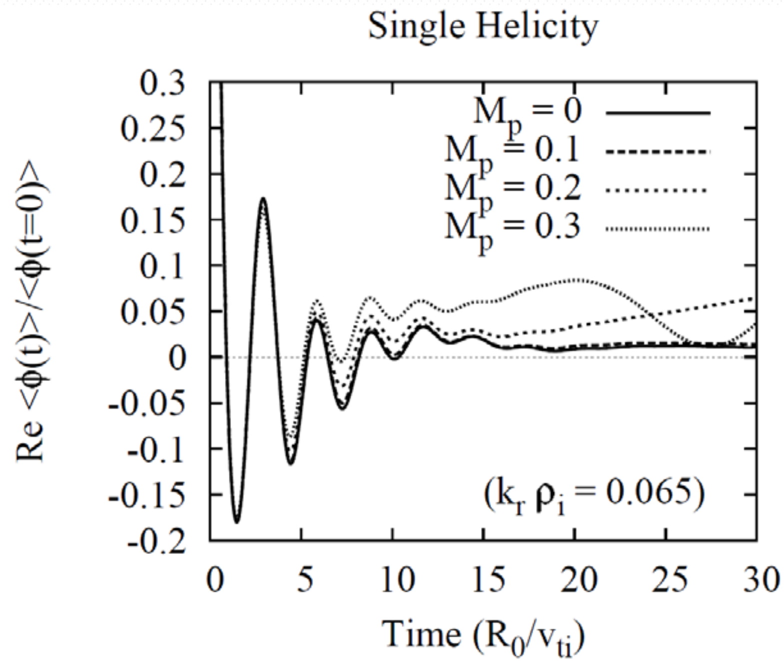
α-dependence

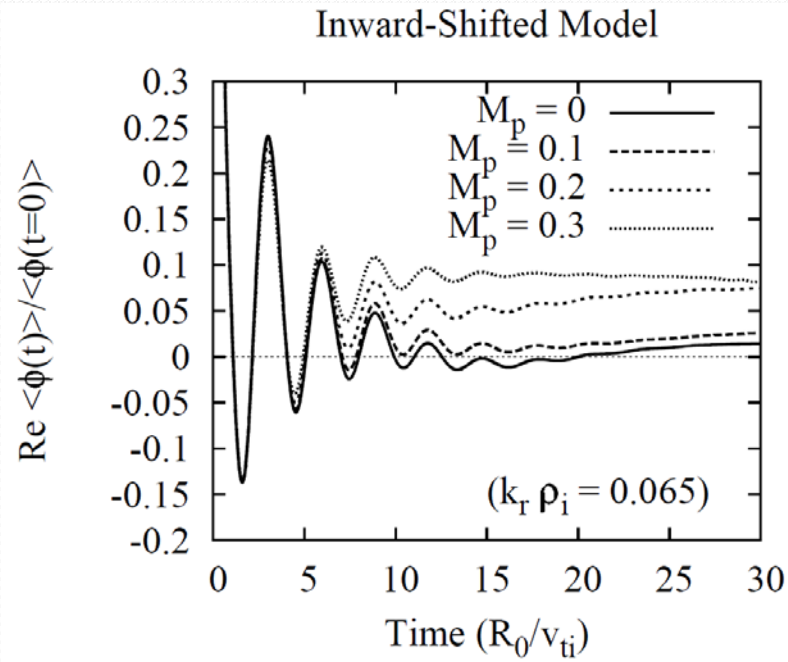
$\omega_\theta = -cE_r/r_0B_0$

$\alpha = \theta - \varsigma/q$

- Even if the zonal-flow potential is independent of α, α-dependence of δf appears through $\mathbf{v}_\mathrm{d}$ term *etc*.
- Symmetry of E_r => - E_r & α => - α is kept.

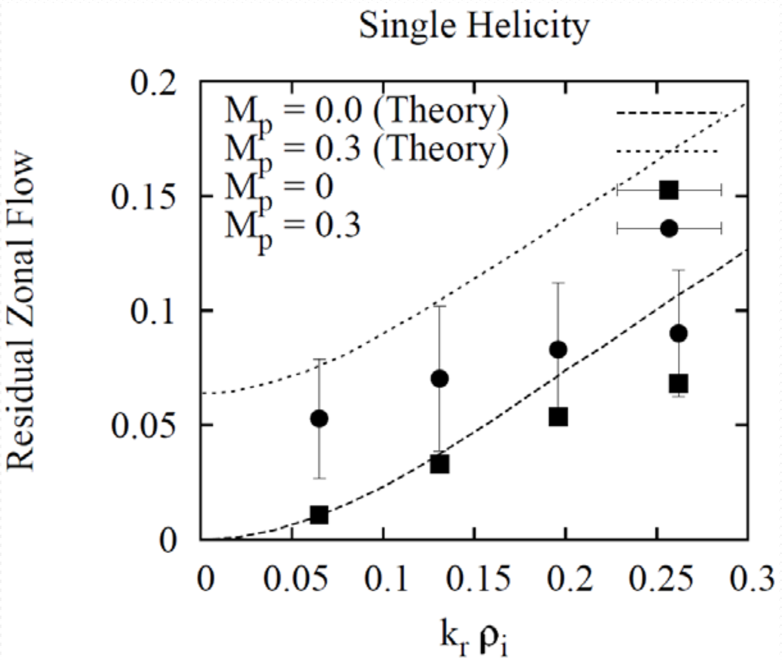
GKV Simulation of ZF Enhancement by Equilibrium-Scale E_r

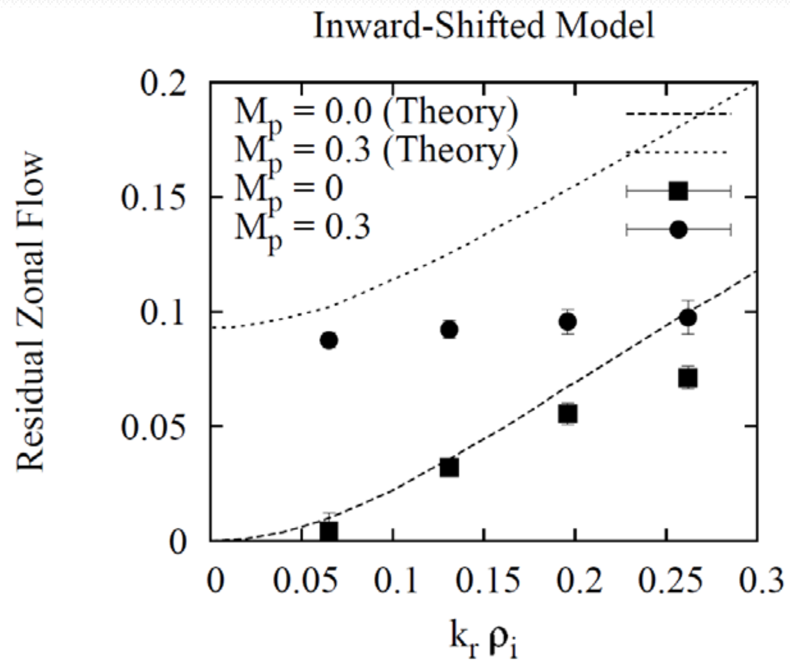




- Single helicity model
  $\varepsilon_h = \varepsilon_t = 0.1$ and $\varepsilon_- = \varepsilon_+ = 0$
- Inward-shifted LHD model
  $\varepsilon_h = \varepsilon_t = 0.1$, $\varepsilon_- / \varepsilon_t = -0.8$, and $\varepsilon_+ / \varepsilon_t = -0.2$

k_r-dependence of Residual Zonal-Flow Levels

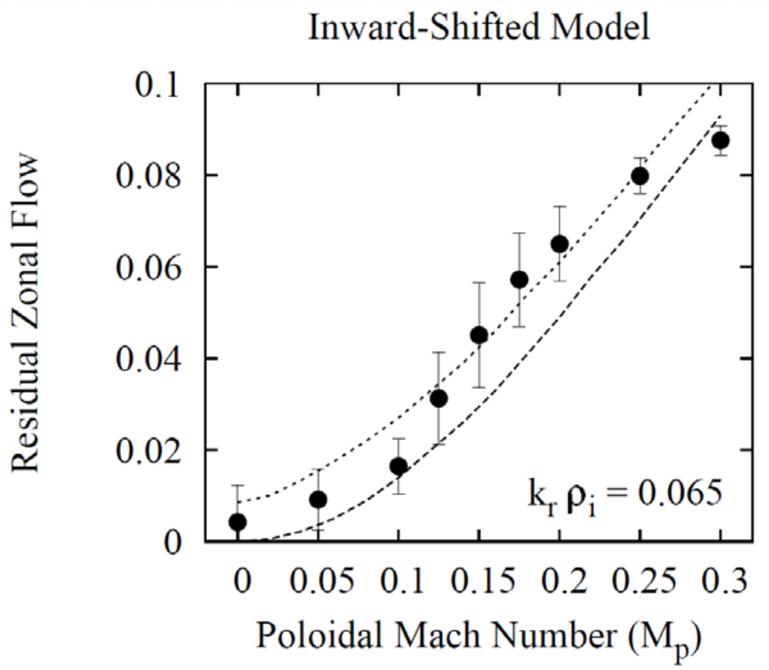




- The residual level with small k_r vanishes for $M_p = 0$, but remains finite for non-zero M_p.
- Stronger enhancement of the ZF response by E_r for the inward-shifted case.

M_p-Dependence of ZF Response

- Residual ZF amplitude increases with the poloidal Mach number, M_p, in agreement with the theoretical estimate



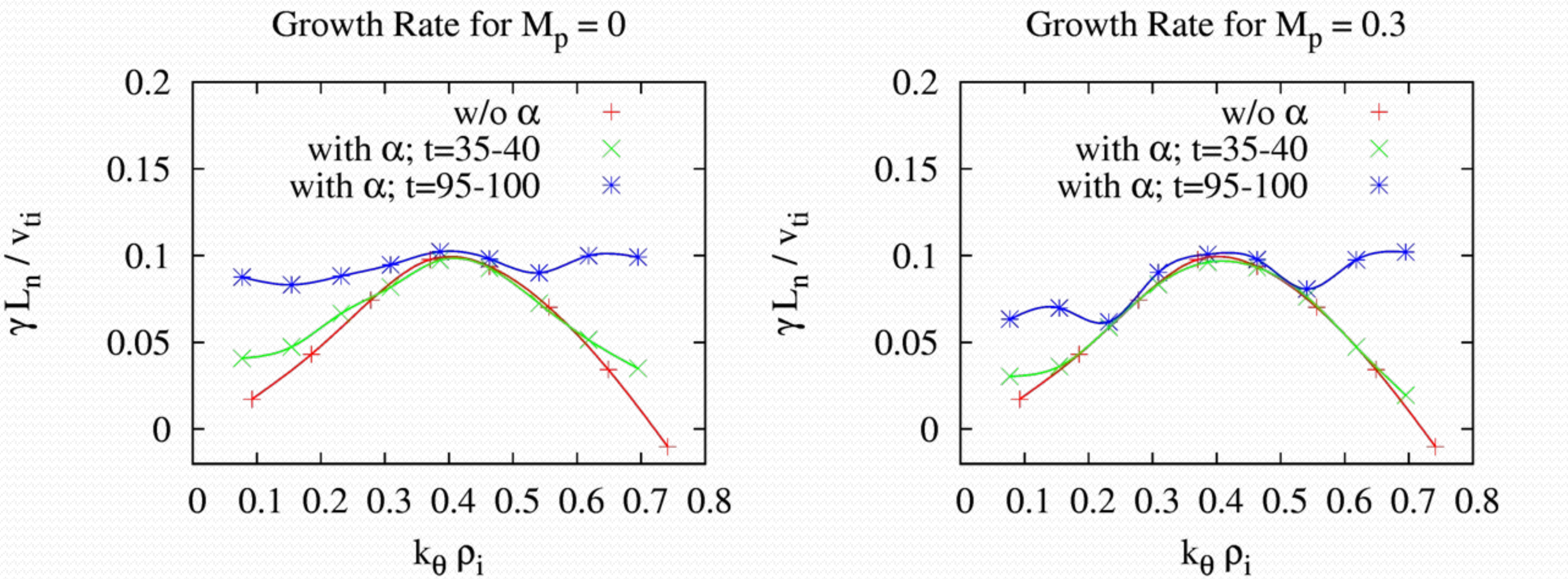
- M_p increases with the ion mass for the same E_r and T_i
  - Neoclassical transport analysis predicts almost the same E_r and T_i for H and D discharges

Isotope effect on ZF response

ITG mode simulations for helical systems with α-dependence and E_r

Linear GK simulations of ITG modes in helical systems with α-depend.

- The field-line-label dependence is incorporated into terms related to $k_r v_d$ and Ω_i in the GKV code.



- Linear growth rates measured at different time
  (before and after the mode coupling appears through α)
- Radial electric field does not much influence the linear ITG growth.

Summary

- Zonal-flow response in helical system is increased
  by slowing the radial drift of trapped particles
  or by imposing the equilibrium-scale E_r .
- Shielding effect of helical-ripple-trapped particles is improved by helical field optimization as well as E_r.
  - New GKV simulations confirm enhancement of zonal-flow response by E_r.
- The results suggests stronger ZF in the inward-shifted configuration with E_r for heavier ion mass.
- ITG mode simulations for helical systems with the field-line-label dependence have been tried.
- Nonlinear simulation with E_r is currently in progress.