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A New Hybrid Model for Efficient Simulation of Ion Scale Electromagnetic Turbulence in Tokamak Plasma

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ABSTRACT

- A new hybrid gyrokinetic model is developed and implemented for the electromagnetic turbulence simulations.
- In this model, a massless fluid model is adopted for passing electrons, while the conventional gyrokinetic model and the bounce kinetic model are applied to ions and trapped electrons, respectively.
- Linear growth rates of ITG, TEM and KBM are benchmarked with other numerical codes, which shows reasonable agreement.
- The stabilizing effect of plasma elongation on KBM is studied by using this model.

BACKGROUND

- There are a lot of difficulties in developing a feasible simulation model for electrons, mainly due to their fast time scale compared to the ion dynamics.
- A mixture of the bounce averaged model for trapped electrons and a massless fluid model for passing electrons were suggested previously. [Hinton F.L. et al., PoP (2003)]
- In this work, the model is implemented numerically into the gyrokinetic code gKPSP and tested for the linear growth rate of electromagnetic instabilities.

NUMERICAL METHODS

- **Electron model**

1. Continuity equation

$$
\begin{aligned}
\frac{\partial}{\partial t}\delta n_e &= \left[\mathbf{B_0}+\delta\mathbf{B}_\perp\right]\cdot\nabla\left(\frac{\delta j_{\parallel e}}{e_c B_0}\right)+\frac{1}{m_e|\Omega_e|B_0^2}\mathbf{B_0}\times\nabla B_0\cdot\nabla\left(\delta P_{\perp e}+\delta P_{\parallel e}\right)\\
&+\frac{\nabla\times\mathbf{B_0}}{m_e|\Omega_e|B_0^2}\cdot\left[\left(\delta P_{\perp e}-\delta P_{\parallel e}\right)\nabla B_0+B_0\nabla\delta P_{\parallel e}\right]-c\frac{\mathbf{B_0}\times\nabla\Phi}{B_0^2}\cdot\nabla\left(n_{e0}+\delta n_e\right)\\
&-c\frac{n_{e0}+\delta n_e}{B_0^2}\left[2\frac{\mathbf{B_0}}{B_0}\times\nabla B_0+\nabla\times\mathbf{B_0}\right]\cdot\nabla\Phi
\end{aligned}
$$

2. Faraday's law combined with Ohm's law

$$
\frac{1}{c}\frac{\partial}{\partial t}A_\parallel = \frac{T_{e0}}{e_c B_0}\delta\mathbf{B}_\perp\cdot\nabla\left(\ln n_{ep0}\right)+\frac{\mathbf{B_0}+\delta\mathbf{B}_\perp}{B_0}\cdot\left[\frac{T_{e0}}{e_c}\nabla\left(\frac{\delta n_{ep}}{n_{ep0}}\right)-\nabla\Phi\right]
$$

- **Time integration method**

: The IMEX (implicit-explicit) Runge-Kutta algorithm is used to mitigate the severe time step restriction related to the shear Alfven wave propagation.

1. stiff linear parts of the field equations -> treated by the implicit method
2. nonlinear parts -> treated by the explicit method

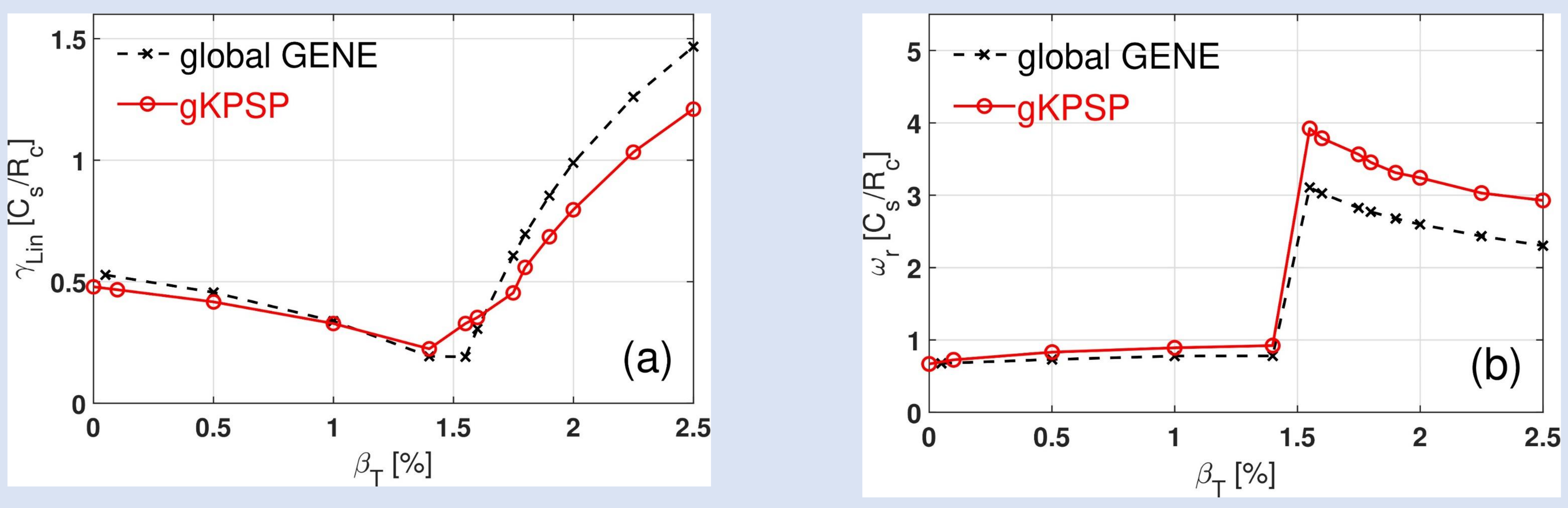

Fig 1. (a) γ_{Lin} (b) ω_{real} of ITG/KBM with varying plasma β

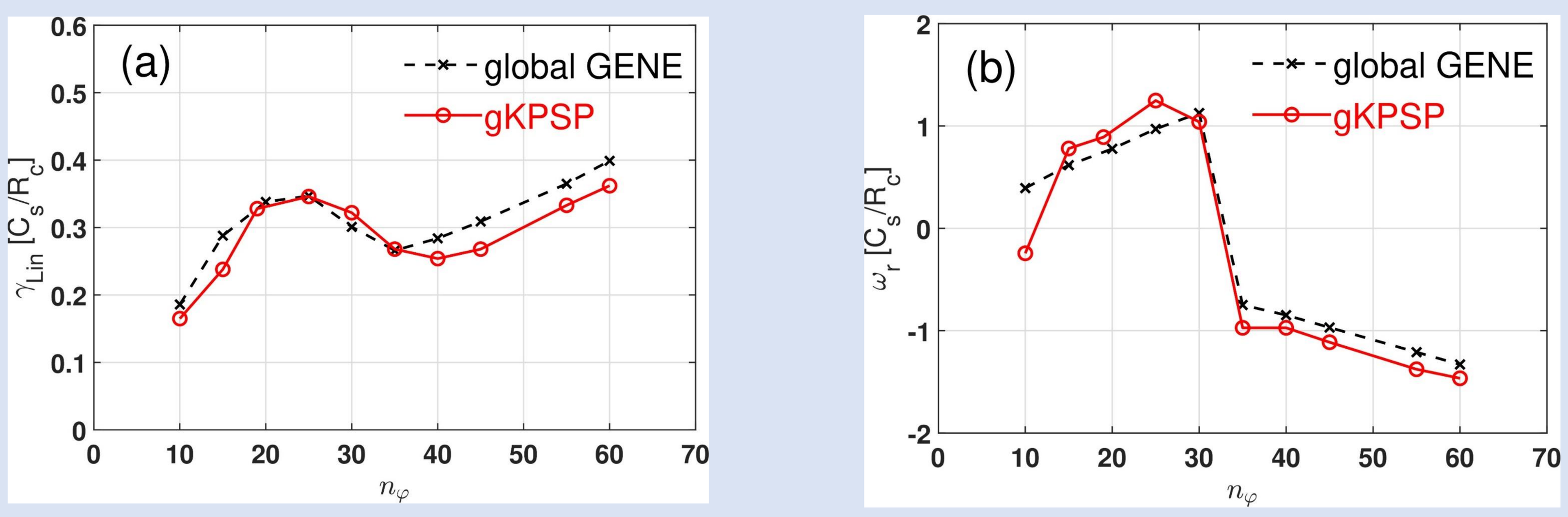

Fig 2. (a) γ_{Lin} (b) ω_{real} of ITG/TEM with varying toroidal mode number

RESULT

- **γ_{Lin} benchmark for ITG-TEM-KBM**

: The linear growth rates γ_{Lin} of ITG-TEM-KBM are benchmarked with GENE code results. [Görler, T. et al., PoP (2016)]

1. ITG/KBM with varying plasma β : Fig 1.
2. ITG/TEM with varying toroidal mode number : Fig 2.

: As can be seen in Fig 1 & 2, the newly developed model shows reasonable agreement with GENE results.

- **Stabilizing effects of elongation**

: The elongation κ has a stabilizing effect on KBM, as shown in Fig 3 (a).

: As κ increases, the magnitude of parallel wave number $k_\parallel^2$ also increases, which is shown in Fig 3 (b).

: Since $k_\parallel^2$ has a stabilizing effect on KBM [Kim J. et al., Phys. Fluids (1993)], the increased $k_\parallel^2$ is consistent with the stabilizing effect of the elongation.

- **Linear TAE simulation**

: The growth rate of TAEs driven by varying fast ion energies is tested with the parameters from [Könies A. et al., NF (2018)], which is shown in Fig 4.

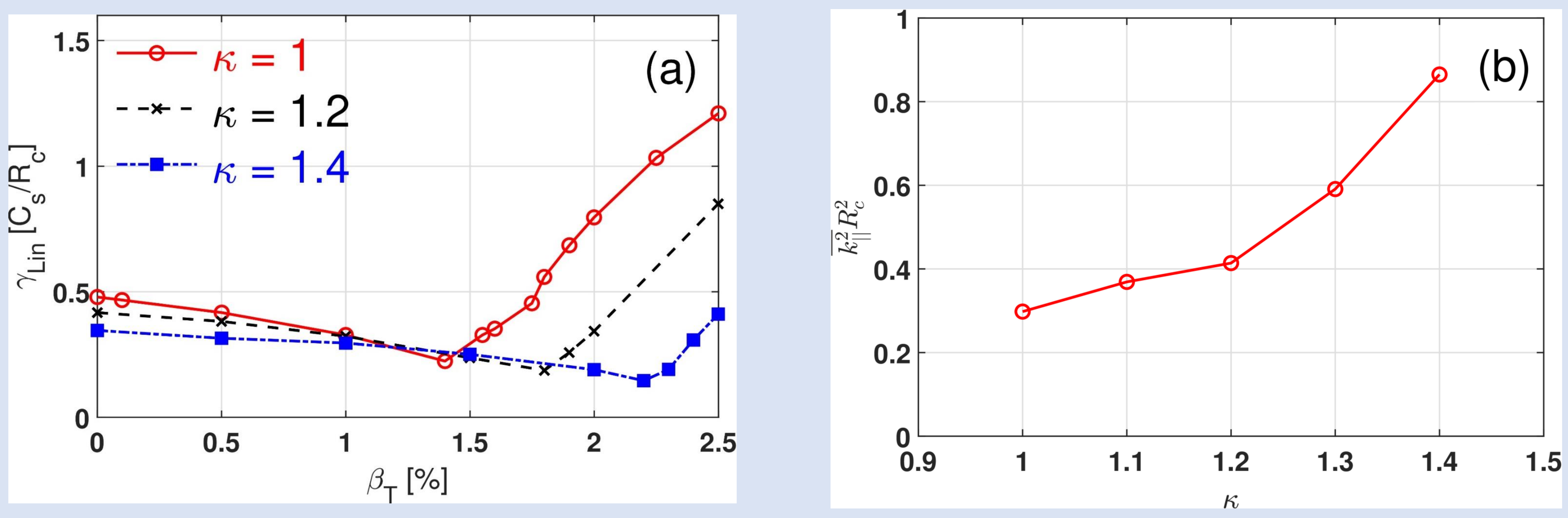

Fig 3. (a) γ_{Lin} of ITG/KBM with different κ

(b) the magnitude of parallel wavenumber with different κ

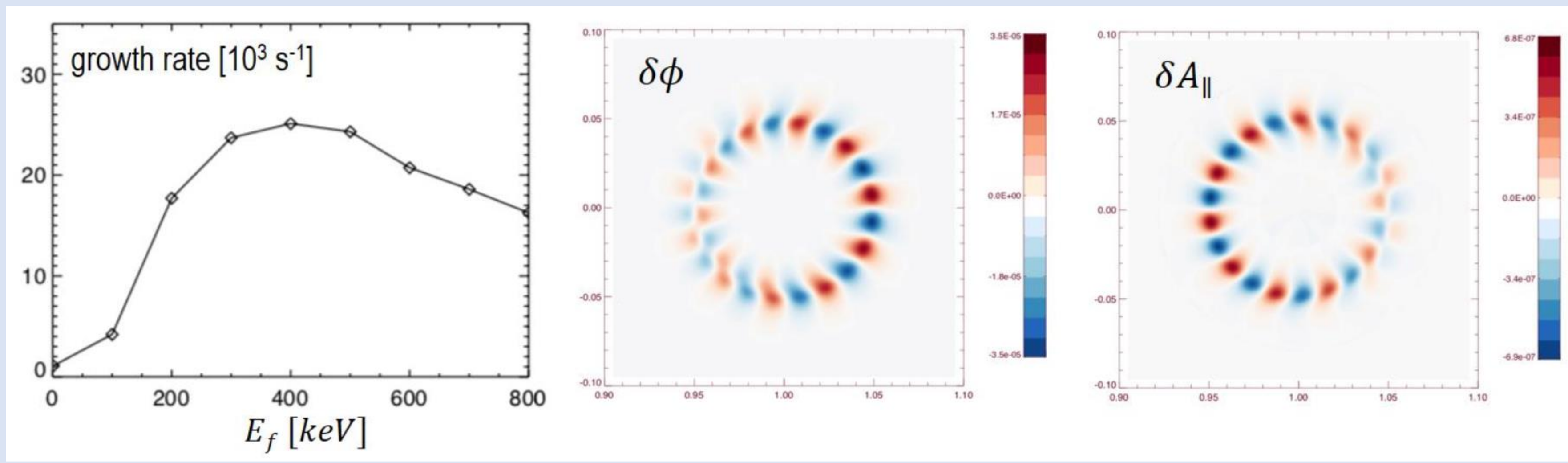

Fig 4. left : γ_{Lin} of TAE with varying temperature of fast ions

middle & right : electrostatic and electromagnetic potential, respectively

CONCLUSION

- A new hybrid electromagnetic scheme with a massless fluid model for passing electrons is implemented numerically.
- Benchmarks for linear growth rates with other codes show reasonable agreement.
- Elongation of magnetic geometry is shown to have a stabilizing effect on the KBM linear instability, which is consistent to the broadened $k_\parallel$ spectrum with higher elongation.
- A nonlinear scheme with this hybrid model is under development.

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