US-China collaborations on development and application of GTC for fusion simulations

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GTC Team
Highlights on recent US-China collaborations on GTC

• Collaborative GTC code development
  ✓ Stellarator, tokamak with 3D equilibrium, field reversed configuration (FRC)
  ✓ High frequency modes: ICE, CAE, GAE, LHW, IBW
  ✓ High performance computing

• GTC physics applications
  ✓ Microturbulences & neoclassical transport
  ✓ Energetic particles & Alfven eigenmodes
  ✓ MHD modes: kink, collisionless, resistive & neoclassical tearing modes

• Productivity since 2017
  ✓ 28 US-China joint papers
  ✓ 18 PhD: 3 UCI/PU, 4 PKU (Prof. Yian Lei), 7 USTC/IOP (Prof. Wenlu Zhang), 4 ZJU (Prof. Yong Xiao)
Outlines

• Microturbulences & neoclassical transport in tokamak with RMP and stellarator
• Energetic particles & Alfven eigenmodes
• MHD modes and high frequency modes
How Does 3D RMP Affect Edge Microturbulence?

I. Can 3D fields with closed flux-surfaces enhance turbulent transport?
II. Role of magnetic islands and stochastic fields?
III. Indirect effects on microturbulence, e.g., radial electric field shear?

- GTC simulations find 3D RMP fields with closed flux-surfaces do not enhance turbulent transport
  
[I. Holod, et al, Nuclear Fusion 57, 016005 (2017)]
II. Resonant Responses Generate Magnetic Islands & Stochastic Fields

- Poincare plots of RMP magnetic fields
- Magnetic island size smaller than ion gyroradius
  - ✓ No ion responses
  - ✓ Enhanced electron particle flux is non-ambipolar
II. Magnetic Islands and Stochastic Fields Can Modify Radial Electric Field by Neoclassical Transport

- GTC simulations find that electron particle flux due to RMP flutter transport causes little density pump out.
- However, non-ambipolar flutter transport induces rapid changes in radial electric field, which damps toroidal rotation.

*J. Y. Fu et al, 2021*
III. RMP Induces Changes of Plasma Profiles

- DIII-D shots with \( n=2 \) RMP [Nazikian et al, PRL2015]
  - 158104.1350: ELMing w/o RMP
  - 158103.3750: ELMing w/ RMP
  - 158103.3050: ELM suppression
III. GTC Simulations Show That Turbulence Spreads to Pedestal Top

- Linear eigenmodes (*upper panels*) form inside pedestal top
- During ELM suppression, turbulence spreads to $q=4$ surface (*red circle*) after *nonlinear* saturation (*lower panels*) due to weaker ExB shear
- Transport in pedestal top increases

Neoclassical and Turbulent Transport in Stellarators

- Intrinsically 3D stellarator is an attractive fusion reactor concept with steady state operation and reduced risk of disruptions since there is minimal plasma current
- What are properties of turbulent transport and energetic particle confinement in stellarators optimized for neoclassical (collisional) transport?
- GTC simulations of ion temperature gradient (ITG) instability in W7-X agree well with EUTERPE
First nonlinear global gyrokinetic simulation of ITG microturbulence in LHD & W7-X

- Neoclassical and turbulent transport intrinsically coupled in 3D equilibrium of stellarators and tokamak with RMP, which requires full flux-surface and radially non-local simulation
- GTC simulations of ITG microturbulence in LHD & W7-X find role of zonal flows and turbulence spreading

**Effects of Ambipolar Electric Field on Microturbulence in W7-X**

- GTC neoclassical simulation of ion and electron simultaneously; Radial electric fields calculated self-consistently

- Ambipolarity ($\Gamma_i \sim \Gamma_e$) radial electric fields $E_r$ in W7-X consistent with other codes (e.g. DKES) \[Wolf et al, NF 57, 102020 (2017)\]

- Ambipolar electric fields strongly suppress ITG turbulence in electron root, but modest effects in ion root

\[J. Y. Fu et al, PoP2021\]
**Helically Trapped Electron Mode (HTEM) in W7-X**

- GTC global simulations find a new trapped electron modes excited by helically trapped electrons in W7-X stellarator

![Diagram](image)

[J. Nicolau et al, 2021]
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Integrated Simulations of Energetic Particles

- Integrated simulations of energetic particle needed for burning plasmas
- V&V of SciDAC ISEP Center: UCI, GA, PPPL, ORNL, LBNL, LLNL, PU, UCSD
- Good agreement for reversed shear Alfven eigenmodes (RSAE)
- Frequency agrees better with experiment at 790ms; Simulations use profiles at 805ms; uncertainty in q measurement

GTC simulation of low-frequency modes in DIII-D

- GTC simulations find beta-induced Alfvén eigenmode (BAE) and a low-frequency mode (LFM) co-exist in DIII-D
- LFM is excited without fast ions and has a frequency inside the gap of beta-induced Alfvén-acoustic eigenmode (BAAE)
- GTC finds that LFM is an interchange-like electromagnetic mode excited by non-resonant drive of pressure gradients
- Compressible magnetic perturbations, which are neglected in most of GK simulations, increases growth rate of LFM & BAE
- Trapped electrons and equilibrium current have modest effects on the BAE and LFM
Suppression of Alfvén eigenmodes by microturbulence

- GTC simulations find that (RSAE) saturated amplitude and EP transport level are an order of magnitude higher than experimental observations.
- In simulations coupling micro-meso scales, RSAE amplitude and EP transport are greatly reduced to experimental level due to zonal flow and EP scattering by ITG microturbulence.
- Resulting RSAE mode structure and microturbulence intensity agree very well with experimental measurements using ECE) and BES.

P. Liu et al, 2021
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V&V of GTC Simulation of Kink Instability in DIII-D

- Microscopic kinetic effects often play important roles in macroscopic MHD modes
- GTC simulations in MHD limit of internal kink agree well with MHD codes
- GTC gyrokinetic simulations find that kinetic effects significantly reduce growth rate
- GTC simulations of 2000 DIII-D experiments used in deep learning model FRNN for real-time SGTC [G. Dong, X. Wei, 2021]
- DOE FES 2022 theory milestone on prediction of $\alpha$-particle transport in ITER: microturbulence, meso scale AE, MHD modes
- Next step: benchmark for fishbone and NTM simulations

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G. Brochard et al, 2021
GTC NTM simulations qualitatively agrees with Fitzpatrick’s theory

\textit{S. Sun et al, 2021}

\textit{Fitzpatrick PoP 199, NTM growth rate:}

- In small island limit: \( I_1 \left( \frac{r_s}{W} \right) \frac{d}{d(t/\tau_R)} \left( \frac{W}{r_s} \right) \approx \Delta' r_s \left( \frac{r_s}{W} \right) + 2.88 \sqrt{\varepsilon_s} \frac{\beta_s'}{s_s} \left( \frac{r_s}{W_c} \right)^2 \)

- In large island limit: \( I_1 \left( \frac{r_s}{W} \right) \frac{d}{d(t/\tau_R)} \left( \frac{W}{r_s} \right) \approx \Delta' r_s \left( \frac{r_s}{W} \right) + 9.26 \sqrt{\varepsilon_s} \frac{\beta_s'}{s_s} \left( \frac{r_s}{W} \right)^2 \)

- Unified: \( I_1 \left( \frac{r_s}{W} \right) \frac{d}{d(t/\tau_R)} \left( \frac{W}{r_s} \right) \approx \Delta' r_s \left( \frac{r_s}{W} \right) + 9.26 \sqrt{\varepsilon_s} \frac{\beta_s'}{s_s} \left( \frac{r_s}{W} \right)^2 + 9.26 \varepsilon_s \frac{s_s}{W^2 + W_d^2}, \text{ here } W_d = 1.8 W_c \)

GTC's simulation uses HL-2A shot #11727 reconstructed equilibrium.
GTC simulation using fully kinetic ion and drift kinetic electron

- Simulation model
  - Fully kinetic (6D) Vlasov equation for ions (FKi)
  - Drift kinetic equation for electrons (DKe)
  - Poisson equation for electrostatic potential
  - Parallel Ampere’s law for parallel vector potential
  - Perpendicular electron force balance for compressible magnetic perturbation

- Verification of linear simulation of CAE/ICE
  - Massless electron, perpendicular propagation
  - Simulation with all $k_\perp$ exhibits CAE/ICE (upper panel)
  - Simulations with a single $k_\perp$ agree with dispersion relation from kinetic theory (lower panel)

Y. Yu et al, 2021
GTC simulation of ICE excitation by $\alpha$-particles

- Magnetoacoustic cyclotron instability (MCI) driven by $\alpha$-particles with population inversion
- Higher harmonics excited by higher $\alpha$-particle density $n_\alpha$ (left panel)
- Growth rate $\gamma \propto \sqrt{n_\alpha}$ in qualitative agreement with Dendy PF1992 theory (right panel)
- Next step: verification of GAE/CAE with $k_\parallel \neq 0$; benchmark with HYM for GAE/CAE

![Graph showing growth rate $\gamma$ vs. $\omega/\Omega_i$ and $\sqrt{n_\alpha/n_i}$]
GTC physics models & applications

• Global integrated simulation of nonlinear interactions of multiple kinetic-MHD processes

• Four kinetic species: thermal ion & electron, fast ion & electron
  ✓ Gyrokinetic thermal & fast ion, drift kinetic thermal & fast electron
  ✓ Fluid-kinetic hybrid electron model, conservative scheme for thermal electron
  ✓ Fully kinetic (6D) ion
  ✓ Shifted Maxwellian & anisotropic slowing down distribution function

• Three fluid models: reduced resistive MHD, massless & finite-mass electron fluid model

• $\delta f$ & full-f method, compressible magnetic perturbation, equilibrium current

• Microturbulence: drift-Alfvenic instabilities, collisionless & drift tearing modes

• MHD: Alfven eigenmodes, kink, resistive & neoclassical tearing modes

• Neoclassical transport: pitch-angle scattering, Fokker-Planck collision operators

• High frequency waves: ICE, CAE, LHW, IBW
GTC geometry and computing capability

- Global 3D toroidal geometry for tokamak, stellarator, cylinder
- Magnetic equilibrium geometry from EFIT, VMEC, M3D-C1, s-a model
- Boozer coordinates, global field-aligned mesh
- FD & FEM for gyrokinetic Poisson equation using Pade approximation, integral form solver
- Sparse matrix solver: amgX, hypre, PETSc
- Synthetic diagnostics: SDP (ECE & ECEI)
- Three levels of parallelization
  - ✔ MPI toroidal domain decomposition
  - ✔ MPI particle decomposition
  - ✔ Loop level: OpenMP/OpenACC

[W. Zhang et al, SC2018]


8. Particle simulation of radio frequency waves with fully-kinetic ions and gyrokinetic electrons, Jingbo Lin, Wenlu Zhang, Pengfei Liu, Zhihong Lin, Chao Dong, Jintao Cao, and Ding Li, Nuclear Fusion 58, 016024 (2018).


23. Verification of Energetic-Particle-Induced Geodesic Acoustic Mode in Gyrokinetic Particle Simulations, Yang Chen, Wenlu Zhang, Jian Bao, Zhihong Lin, Chao Dong, Jintao Cao, and Ding Li, Chin. Phys. Lett. 37, 095201 (2020).


