Microinstability simulations for stellarators involving kinetic electrons and realistic profiles with the global PIC code EUTERPE

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Global gyrokinetic code EUTERPE

- originally developed at CRPP Lausanne (G. Jost, 2000), since then at IPP
- close relative of GYGLES, ORB5, NEMORB
- gyrokinetic particle-in-cell (PIC) code utilizing $\delta f$-method for noise reduction
- fully global = full flux surface & full radius (annulus possible)
- linear/nonlinear regime possible
- electrostatic/electromagnetic version possible
- multiple species (e.g. ions, electrons, fast ions/impurities)
- pitch-angle collision operator
- phase-factor extraction for linear simulations
- coupling to models of different complexity (FLU-EUTERPE, CKA-EUTERPE, ...)
- different applications by several users
Profiles & Equilibria in Global Simulations

local simulations

- widely used since numerical effort comparably low
- offer themselves as an ideal tool for parameter studies
- parameters and gradients can be varied easily
- BUT: free variation of gradients can lead to inconsistent and unrealistic profiles
- THEREFORE: careful choice and documentation of assumptions required

global simulations

- desirable BUT offer multiple challenges
- numerical effort much larger
- local variation of parameters or gradients will always affect entire profiles
- parameter or gradient variations can result in unrealistic global profiles
- changing profiles may lead to inconsistency with equilibrium assumptions
Profiles & Equilibria in Global Simulations

• most global simulations so far are done with *artificial* profiles, i.e.
  • gradients limited to radial range avoiding difficult regions (core, edge)
  • local gradients can be inconsistent with actual profiles
  • profiles not consistent with underlying equilibrium pressure profile

• *realistic* profiles
  • may have extended gradients not avoiding difficult regions
  • can be experimental profiles
  • are interlinked and consistent with equilibrium pressure profile
Profiles and Gradient Scans in Global Simulations

- Gradient scans are routinely used for stability studies.
- Density and temperatures in a given equilibrium depend on each other.
- Variation of one profile may affect other profiles and/or the equilibrium.
- Gradient scans correspond to unique trajectories in configuration space.
- Vast variety of profile variation schemes (trajectories) possible.
- Different schemes may require different effort (economy?).
- Underlying assumptions need to be disclosed for correct interpretation.

Example for simple gradient variation scheme follows.
Example: Simple Pressure-Preserving Scheme

- quasi-neutral and single-charged plasma with $T_e = T_i = T$

$$p(s) = n_0 T_0 f(s)$$

- simple decomposition of pressure according to

$$n = n_0 f^\chi \quad \text{and} \quad T = T_0 f^{1-\chi}$$

- results in simple relations for drive $\kappa$ and stability parameter $\eta$

$$\kappa_n = \left| \frac{n'}{n} \right| = \chi \left| \frac{f'}{f} \right| , \quad \kappa_T = \left| \frac{T'}{T} \right| = (1 - \chi) \left| \frac{f'}{f} \right| \quad \text{and} \quad \eta = \frac{\kappa_T}{\kappa_n} = \frac{1 - \chi}{\chi}$$

- enables gradient scan within a given equilibrium

- for more general case one may introduce *profile-separation function* $g(s)$

$$p = ng^{-\chi} (T_e + T_i) g^{\chi}$$
Pressure-Preserving Scheme (Ctd.)

- parameter $\chi$ allows consistent variation of gradients for given equilibrium
- variation of pressure profile leads to new equilibrium
- introduce *peaking parameter* $\lambda$ to vary pressure: $\ p \rightarrow p^\lambda$
- additional assumption: renormalize pressure to keep $\langle \beta \rangle$ fixed
- 2D-scan over density and temperature gradients = scan over parameters $\chi$ and $\lambda$
Profiles in Pressure-Preserving Gradient Scan

- pressure-preserving gradient scan over $\chi$ for given equilibrium ($\lambda = 1.0$)

- pressure profile scan with $\lambda$ over equilibria with fixed $\langle \beta \rangle$ ($\chi = 0.2$)
- gradient scans ($\chi$) for three different W7-X equilibria ($\lambda$)
- linear ITG growth rates - in different representations
- damping effect of neoclassical electric field $E_r$

$E_r = 0$ :

$E_r \sim p'$ :
Comment on Fourier Filters in EUTERPE

- unique EUTERPE feature: real and complex version available
- complex version (linear problem only) offers possibility for *phase-factor extraction*

\[ \mathbf{X}(\theta, \phi) = \tilde{\mathbf{X}}(\theta, \phi) e^{i(m_0\theta + n_0\phi)} , \quad \tilde{\mathbf{X}}(\theta, \phi) = \sum \tilde{X}_{mn} e^{i(m\theta + n\phi)} \]

- allows strong reduction of grid resolution when dealing with high mode numbers
- define Fourier filter with \([\Delta m, \Delta n]\) around phase-factor \([m_0, n_0]\)
- different filter types available (rectangular, diagonal, ...)
- some simulations found sensitive to type and shape of applied Fourier filter
- early simulations with kinetic electrons were obstructed by spurious modes
- problems could be resolved with tailored Fourier filters
Tailoring Fourier Filters

- \( \nu\)-corridor: \( m\)-\( n\)-domain bounded by lines with \( n = -\nu_{\text{max}}m \) and \( n = -\nu_{\text{min}}m \)
- spurious modes observed at \((m, n)\) outside of \( \nu\)-corridor
- problems were resolved with aligned filter restricted to \( \nu\)-corridor
- final mode localized around flux surface \( s_\ast \) with local \( \nu_\ast \)
- Fourier spectrum distributed around \( n = -\nu_\ast m \)

rectangular filter  aligned filter  simulation
Linear Simulations with Kinetic Electrons - Profiles

- density-temperature gradient ($\chi$) scan for a fixed pressure profile ($T_e = T_i$)
- position of maximum gradients ($T', n'$) is different and varies under scan
- position of maximum drive $\kappa_n$ and $\kappa_T$ is identical and fixed
- stability parameter varies but obeys $\eta = const(s)$

$$f = T :$$

$$f = n :$$
• comparison of kinetic vs. adiabatic electrons in ITG-regime ($\eta = 3$)
• phase-factor scan over $k_\perp \rho(m_0, n_0)$ with small Fourier filter size
• growth rates $\gamma(k_\perp \rho)$ have local maximum at $k_\perp \rho \approx 2$
• behaviour similar to other results (cf. Sánchez et. al 2021)
• adequate time steps used ($\Delta t_{\text{kin}} \leq \Delta t_{\text{ad}}/40$) $\longrightarrow$ good agreement
• notice radial localization of mode (position of maximum density gradient)
○ gradient $(\chi)$ scan over $\eta = \kappa_T/\kappa_n = L_n/L_T$ for fixed pressure profile
○ phase-factor scan over $k_{\perp} \rho(m_0, n_0)$ with small Fourier filter at fixed $\eta$
○ maximum growth rates observed for $k_{\perp} \rho \approx 2$
○ electron-driven modes ($\eta \leq 1$) localized around maximum drive $(\kappa)$ position
○ poloidal shift decreases with $k_{\perp} \rho$?
results for most dominant modes \( (k_\parallel \rho \approx 2) \) at different \( \eta \)

- strong increase of growth rates for \( \eta \leq 1 \)
- electron-driven modes \( (\eta \leq 1) \) localized around maximum drive (\( \kappa \)) position
- poloidal shift smaller for electron-driven modes?

\[
growth rate \\
\eta \times 10^3 \text{ TeV} \\
0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \\
1 \quad 2 \quad 3 \quad 4 \quad 5 \\
\text{frequency} \\
f \times 10^3 \text{ Hz} \\
0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \\
-1 \quad 0 \quad 1 \quad 2 \quad 3 \\
\text{radial position} \\
r \times 10^3 \text{ cm} \\
0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \\
0.5 \quad 0.6 \quad 0.7 \quad 0.8 \\
\text{poloidal shift} \\
\theta \times 10^{-2} \text{ m} \\
0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \\
-0.03 \quad -0.03 \quad -0.03 \quad -0.03
energy transfer over phase space $v_\perp - v_\parallel$ for different $\eta$ and $k_\perp \rho = 2.0$

characteristic 'kidney' shape for ions in ITG regime ($\eta = 3$)

fully developed trapping cone for electrons in TEM regime ($\eta = 0.33$)

trapping cone: $v_\parallel^2/v^2 \leq 1 - B_{\min}/B_{\max}$ (here shown for $s = 1$)

(energy transfer $< 0$: driving / energy transfer $> 0$: damping)
phase space diagrams for phase factor set to different $k_{\perp \rho}$ at $\eta = 1.0$

different (ITG-like, TEM-like) contributions mix into final mode

(energy transfer $< 0$: driving / energy transfer $> 0$: damping)
Summary and Outlook

- global linear simulations with kinetic electrons successfully done with EUTERPE
- different regimes were tested using profiles with consistent gradient variations
- only linear simulations of this type so far but nonlinear simulations in progress
- simulations with realistic parameters require high resolutions
- nonlinear simulations with kinetic electrons much more costly and sensitive
- some electromagnetic simulations for down-scaled cases successful (A. Mishchenko)
- will be used as starting point for further steps