Max-Planck-Institut für Plasmaphysik

Upgrade of GENE-3D to an electromagnetic turbulence code

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Meeting TSVV group 13

MAX PLANCK GESELLSCHAFT

EUROfusion

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- GENE-3D is now able to run simulations with kinetic electrons with reasonable amounts of computational effort
- Furthermore, it is capable of including electromagnetic effects coming from magnetic flutter (perturbed $A_{||}$)

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  $F_\sigma\left(\mathbf{X}, v_{||}, \mu, t\right) = F_{M,\sigma}\left(\mathbf{X}, v_{||}, \mu\right) + F_{1,\sigma}\left(\mathbf{X}, v_{||}, \mu, t\right)$

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- Uses a field-aligned coordinate system:

$$x = \rho_{tor} = \sqrt{\Phi_{tor}/\Phi_{edge}}; \qquad \Phi_{tor} : \text{ Toroidal flux}$$

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- Can perfom simulations of flux-tubes, single flux-surfaces and radially global domains

Gyrokinetic Vlasov-Maxwell system used in GENE-3D (previous)

$$
\begin{aligned}
\frac{\partial F_{1,\sigma}}{\partial t} = & -\left[v_{||}\mathbf{b}_0 + (\mathbf{v}_{\nabla B} + \mathbf{v}_c)\right] \cdot \left(\nabla F_{1,\sigma} + \frac{q_\sigma F_{M,\sigma}}{T_{0,\sigma}} \nabla \mathcal{G}\{\phi_1\}\right) + \frac{\mu}{m_\sigma}\mathbf{b}_0 \cdot \nabla B_0 \frac{\partial F_{1,\sigma}}{\partial v_{||}} \\
& - \mathbf{v}_{E_1} \cdot \left[\nabla \ln(n_{0,\sigma}) + \nabla \ln(T_{0,\sigma}) \left(\frac{m_\sigma v_{||}^2/2 + \mu B_0}{T_{0,\sigma}} - \frac{3}{2}\right)\right] F_{M,\sigma} \\
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\end{aligned}
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Gyroaverage operators:

$\mathcal{G}\{\}$: Push – forward

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Particle drifts:

$$\mathbf{v}_{\nabla B} \equiv \frac{\mu c}{q_\sigma B_0^2}\mathbf{B}_0 \times \nabla B_0, \quad \mathbf{v}_c \equiv \frac{v_{||}^2}{\Omega_\sigma}(\nabla \times \mathbf{b}_0)_\perp$$

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- Works well for adiabatic electron simulations
- Kinetic electron simulations with $\beta = 0$ have severe time step restrictions due to ω_H mode [*]

*Doerk, Hauke, and Frank Jenko. "Towards optimal explicit time-stepping schemes for the gyrokinetic equations." *Computer Physics Communications* 185.7 (2014)

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- Cannot account for electromagnetic effects

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- Explicit time derivative in the RHS makes finite difference scheme unstable
- Previous attemps of GENE by solving GK equation for $g_\sigma = F_{1,\sigma} + \frac{q_\sigma v_{||}}{c}\frac{F_{M,\sigma}}{T_{0,\sigma}}\mathcal{G}\{A_{1,||}\}$ become unstable nonlinearly at high β

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- Final equation:

$$\nabla_\perp^2 E_{||}^{ind} - \frac{4\pi}{c^2}\sum_\sigma q_\sigma^2\int v_{||}^2\mathcal{K}\left\{\frac{F_{M,\sigma}}{T_{0,\sigma}}\mathcal{G}\left\{E_{||}^{ind}\right\}\right\}d^3v = \frac{4\pi}{c^2}\sum_\sigma q_\sigma\int v_{||}\mathcal{K}\{R_\sigma\}\,d^3v$$

Final set of equations

$$\frac{\partial F_{1,\sigma}}{\partial t} = R_\sigma + q_\sigma v_{||} \frac{F_{M,\sigma}}{T_{0,\sigma}} \mathcal{G}\left\{E_{||}^{ind}\right\}$$

$$R_\sigma = -\left[v_{||}\mathbf{b}_0 + (\mathbf{v}_{\nabla B} + \mathbf{v}_c)\right] \cdot \left(\nabla F_{1,\sigma} + \frac{q_\sigma F_{M,\sigma}}{T_{0,\sigma}} \nabla \mathcal{G}\{\phi_1\}\right) + \frac{\mu}{m_\sigma} \mathbf{b}_0 \cdot \nabla B_0 \frac{\partial F_{1,\sigma}}{\partial v_{||}}$$
$$- \mathbf{v}_\chi \cdot \left[\nabla \ln(n_{0,\sigma}) + \nabla \ln(T_{0,\sigma}) \left(\frac{m_\sigma v_{||}^2/2 + \mu B_0}{T_{0,\sigma}} - \frac{3}{2}\right)\right] F_{M,\sigma}$$
$$- \mathbf{v}_\chi \cdot \left(\nabla F_{1,\sigma} + \frac{q_\sigma F_{M,\sigma}}{T_{0,\sigma}} \nabla \mathcal{G}\{\phi_1\}\right)$$
$$- \mathbf{v}_{E_0} \cdot \nabla F_{1,\sigma} + C[F_{1,\sigma}]$$

Gyroaverage operators:

$\mathcal{G}\{\}$: Push – forward

$\mathcal{K}\{\}$: Pull – back

Particle drifts:

$$\mathbf{v}_{\nabla B} \equiv \frac{\mu c}{q_\sigma B_0^2} \mathbf{B}_0 \times \nabla B_0, \quad \mathbf{v}_c \equiv \frac{v_{||}^2}{\Omega_\sigma} (\nabla \times \mathbf{b}_0)_\perp$$

$$\mathbf{v}_{E_0} \equiv \frac{c}{B_0^2} \mathbf{B}_0 \times \nabla \phi_0, \quad \mathbf{v}_{E_1} \equiv \frac{c}{B_0^2} \mathbf{B}_0 \times \nabla \mathcal{G}\{\phi_1\} \rightarrow \mathbf{v}_\chi \equiv \frac{c}{B_0^2} \mathbf{B}_0 \times \nabla \mathcal{G}\left\{\phi_1 - \frac{v_{||}}{c} A_{1,||}\right\}$$

Field equations:

$$\sum_\sigma q_\sigma^2 \int \left(\frac{F_{M,\sigma}}{T_{0,\sigma}} \phi_1 - \mathcal{K}\left\{\frac{F_{M,\sigma}}{T_{0,\sigma}} \mathcal{G}\{\phi_1\}\right\}\right) d^3v = \sum_\sigma q_\sigma \int \mathcal{K}\{F_{1,\sigma}\}\, d^3v$$

$$\nabla_\perp^2 A_{1,||} = -\frac{4\pi}{c} \sum_\sigma j_{1,||,\sigma} = -\frac{4\pi}{c} \sum_\sigma \int v_{||} \mathcal{K}\{F_{1,\sigma}\}\, d^3v$$

$$\nabla_\perp^2 E_{||}^{ind} - \frac{4\pi}{c^2} \sum_\sigma q_\sigma^2 \int v_{||}^2 \mathcal{K}\left\{\frac{F_{M,\sigma}}{T_{0,\sigma}} \mathcal{G}\left\{E_{||}^{ind}\right\}\right\} d^3v = \frac{4\pi}{c^2} \sum_\sigma q_\sigma \int v_{||} \mathcal{K}\{R_\sigma\}\, d^3v$$

Linear electromagnetic tokamak benchmark against GENE

- Verify EM upgrade against x-global version of GENE, performing β-scan presented in [*]

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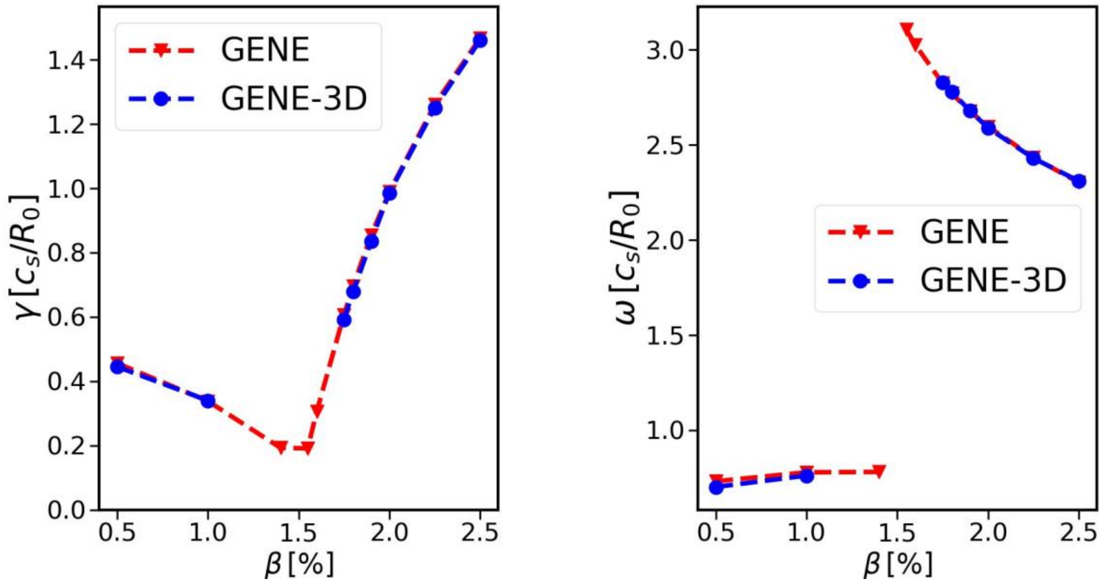
- GENE-3D and GENE show excellent agreement for both, growth rates and frequencies, in ITG as well as KBM regime



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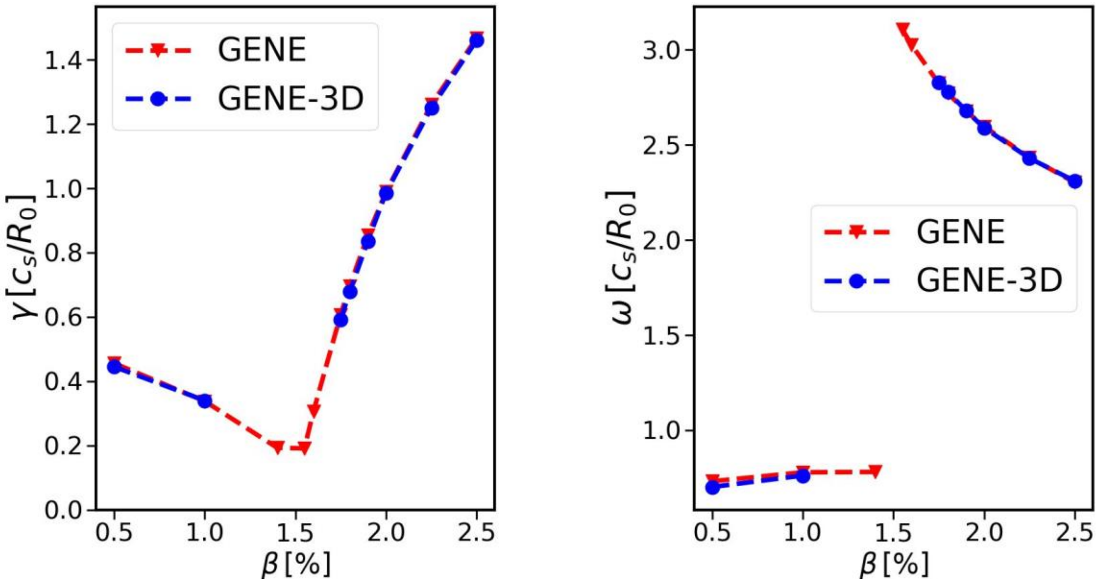
- Nonlinear benchmark was also conducted, but is omitted here for simplicity



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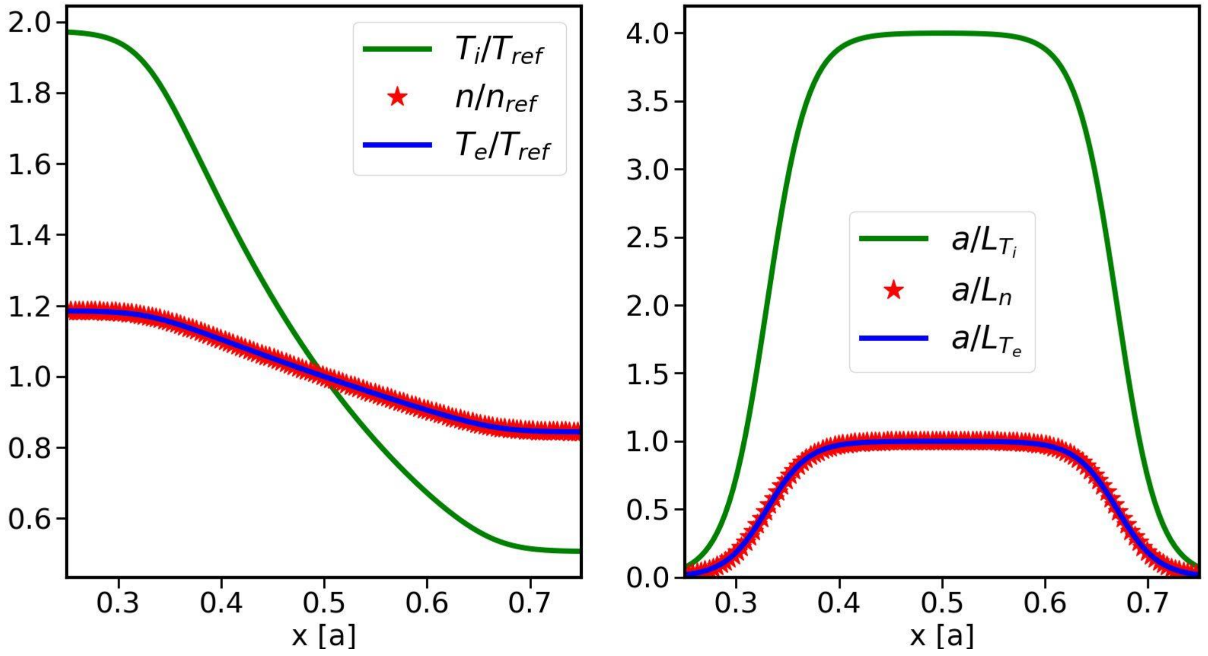
Preliminary: EM ITG turbulence in W7-X



- Use flattop profiles with strong ITG drive
- Standard configuration, geometry consistent with profiles
- Realistic electron mass
- $\rho^*_{ref} = 1/184$
- Smaller ρ^*_{ref} makes the simulation cheaper [c.f. $\rho^*_{\text{realistic}} \sim 1/350$]; realistic ρ^* is still doable

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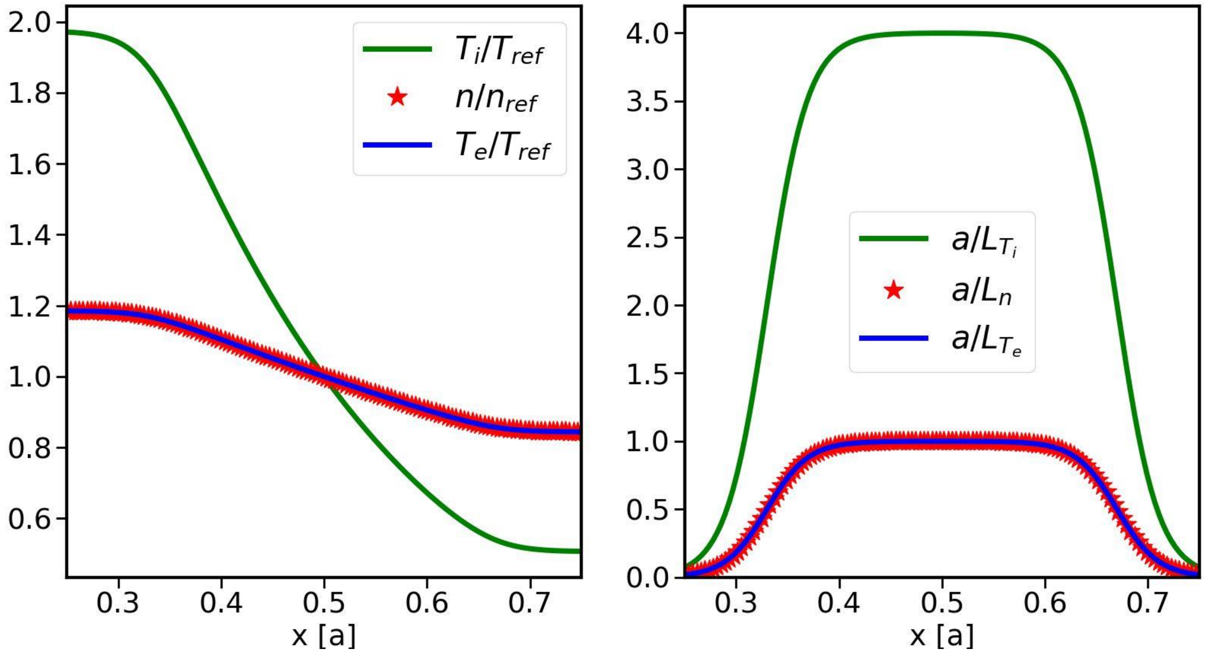

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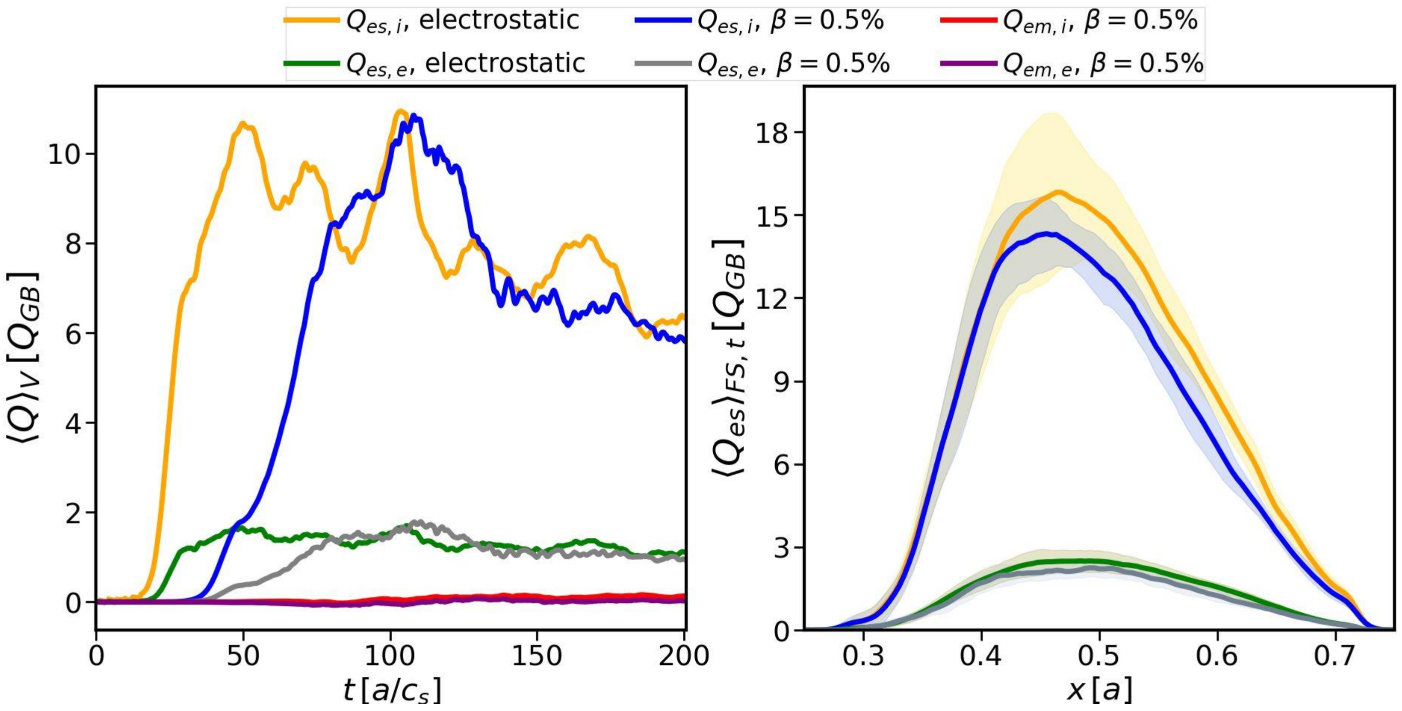
Compare:

1. Kinetic electrons in the "electrostatic limit" $\beta_e(x/a = 0.5) = 10^{-4}$
2. Kinetic electrons with $\beta_e(x/a = 0.5) = 0.5\%$



- Reduction of ion transport channel: Peak value decreases from $(15.8 \pm 2.8)\,\mathrm{Q_{GB}} \rightarrow (14.3 \pm 1.3)\,\mathrm{Q_{GB}}$ through electromagnetic effects

- Electron channel reduced from $(2.5 \pm 0.4)\,\mathrm{Q_{GB}} \rightarrow (2.3 \pm 0.3)\,\mathrm{Q_{GB}}$

$\Rightarrow$ Slight reduction ($\sim 10\%$) in nonlinear heat flux

Ongoing/future work

- D2.1: ”Study the turbulent transport of the main ions and electrons, including the nonlinear interplay between ITG and TEM turbulence in W7-X. This will allow to anticipate fundamental features of turbulence in W7-X OP2 plasmas.”

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Thank you for your attention!