PPPL PRINCETON PLASMA PHYSICS LABORATORY

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Electromagnetic schemes in the global gyrokinetic PIC code XGC for higher-fidelity simulation of long-wavelength modes in the edge

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HBPS High-fidelity Boundary Plasma Simulation

PRINCETON UNIVERSITY

IPP Max-Planck-Institut für Plasmaphysik

NERSC

ECP EXASCALE COMPUTING PROJECT

Abstract

- Two new electromagnetic schemes have been implemented in the global gyrokinetic particle-in-cell code XGC, using gyrokinetic ions and drift-kinetic electrons.
- The two numerical schemes, one explicit and one implicit, have been verified against other global gyrokinetic codes for the ITG-KBM transition.
- The total-f capability of the explicit EM scheme has been used to demonstrate KBM quasi-saturation via self-organization of turbulence and background plasma profiles, while the δf capability has been used to study the effects of magnetic geometry on KBM stabilization in compact tori.
- The well-known numerical *cancellation problem* has not been observed with either scheme, in both the linear and nonlinear simulations that have been performed thus far.

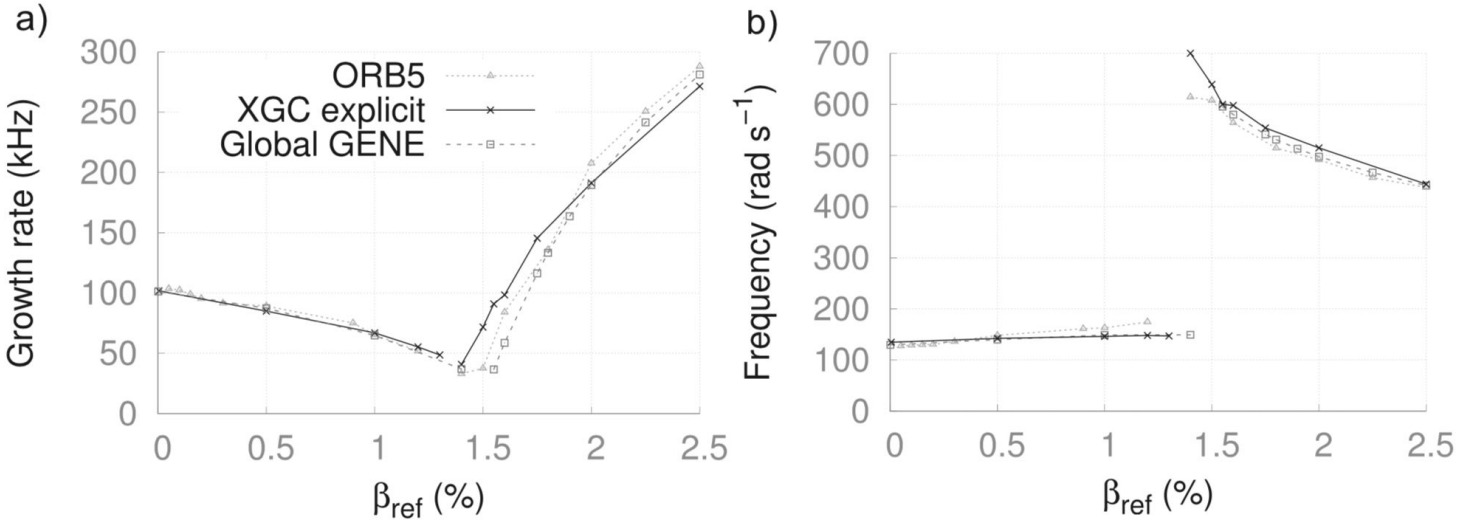
Implicit and explicit EM schemes

Gyrokinetic (GK) formulation	Velocity coordinate	Numerical scheme	Cancellation problem
Symplectic	$v_{\|\|}$	**Implicit**	No
Hamiltonian	$p_{\|\|}$	Explicit	Yes
Mixed	$u_{\|\|}$	**Explicit**	Mitigated

- Implicit EM scheme (B. J. Sturdevant et al., Phys. Plasmas, submitted):
  - Symplectic GK formulation and absence of cancellation problem
- Explicit EM scheme (M. D. J. Cole et al., Phys. Plasmas, 2021):
  - Mixed GK formulation mitigates the cancellation problem.

Verification: ITG-KBM transition (explicit scheme)

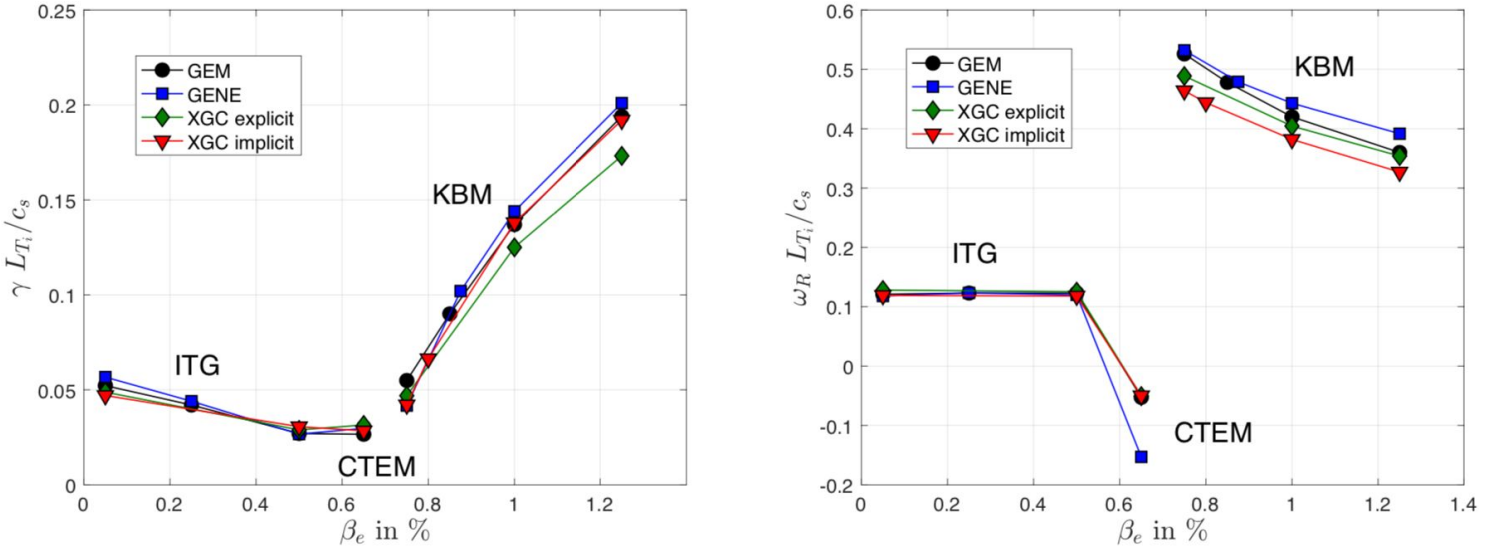
- The explicit EM scheme has been verified against the global gyrokinetic codes GENE and ORB5 for the ITG-KBM transition.
- The case used is a well-known linear benchmark (Görler et al., Phys. Plasmas, 2016) that is closely related to the Cyclone Base Case (CBC) (Dimits et al., Phys. Plasmas, 2000).
- There is good agreement between the three codes, even at high plasma β where the cancellation problem should be most severe.



Growth rates and real frequencies as a function of the reference plasma β.

Verification: ITG-KBM transition (explicit and implicit)

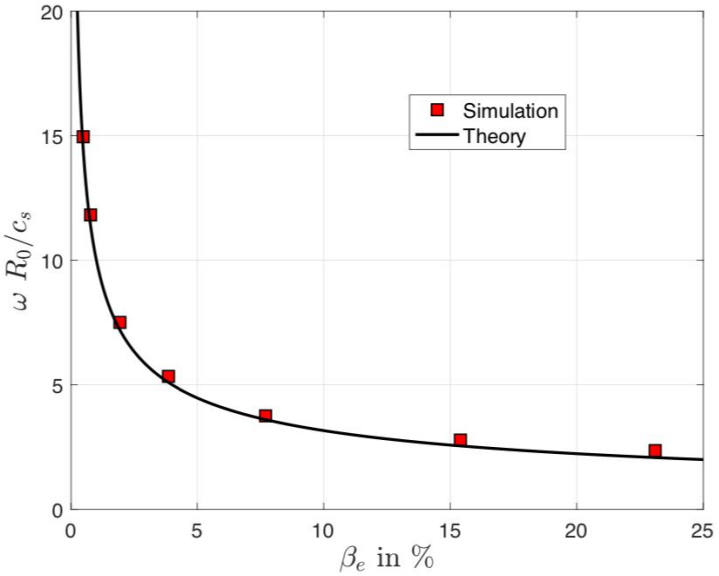
- The explicit and implicit EM schemes have been verified against the global gyrokinetic codes GEM and GENE for another ITG-KBM transition case.
- We refer to this case as the Economical Cyclone Base Case (ECBC), as the ratio of ion gyroradius to tokamak minor radius ρ* is approximately 1/50, compared to approximately 1/180 for the CBC.
- There is good agreement between the four codes, and the cancellation problem is either absent or successfully mitigated.



Growth rates and real frequencies as a function electron plasma β.

Verification: shear Alfvén wave (implicit scheme)

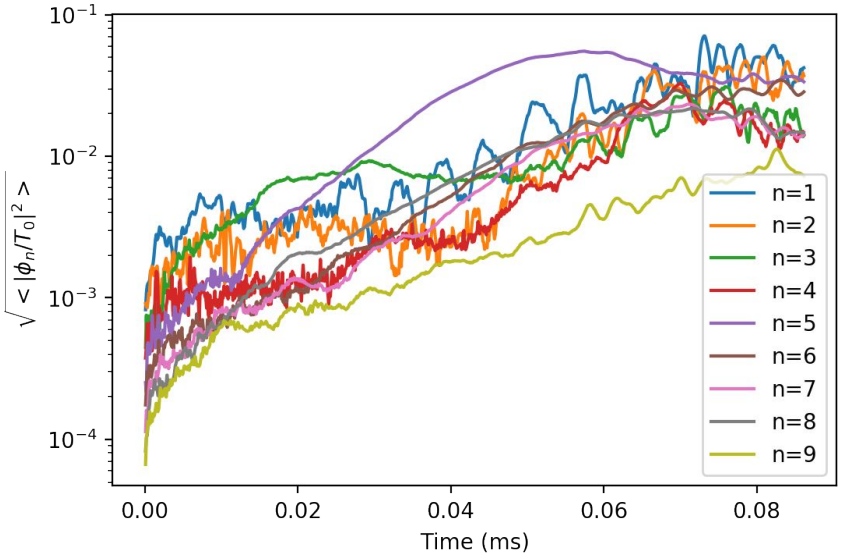
- The implicit EM scheme has been verified for shear Alfvén wave propagation.
- Simulations used a high-β, long-wavelength regime that would not be attainable if the cancellation problem were present.
- There is excellent agreement between simulation and analysis.



Simulated and analytic real frequencies as a function of the electron plasma β.

Total-f profile-consistent KBM quasi-saturation

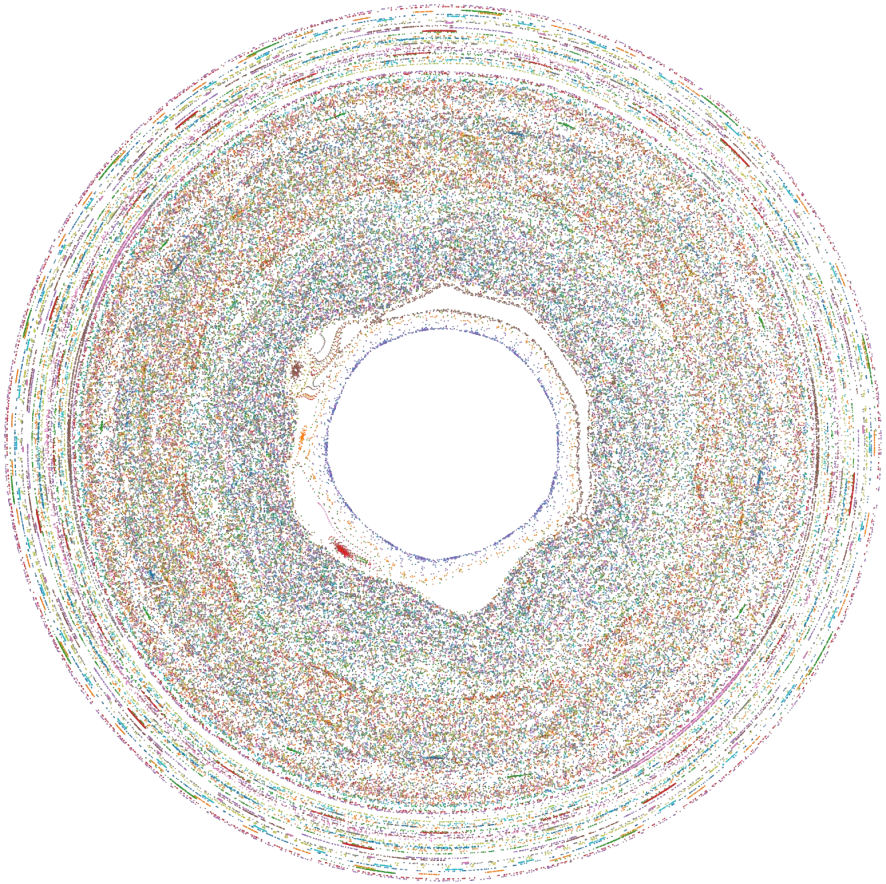
- Local linear δ*f* simulations show explosive growth of KBMs, and these results have guided reduced model codes such as EPED.
- Global δ*f* simulations by the GTC and GKNET codes show nonlinear KBM saturation at high amplitude, while not allowing background profile evolution.
- The total-*f* capability of the explicit EM scheme in XGC has been used for simulations in which KBM turbulence and background profiles evolve together in a self-organized manner.
- The ECBC at β_e=1 is used, and, in order to avoid possible vertical MHD instabilities, axisymmetric magnetic perturbations are not included.
- It is found that background plasma profile relaxation is brought about locally around significant mode rational surfaces, together with $\boldsymbol{E} \times \boldsymbol{B}$ zonal flow generation, which in turn leads to the quasi-saturation of KBMs that is consistent with the source rate.



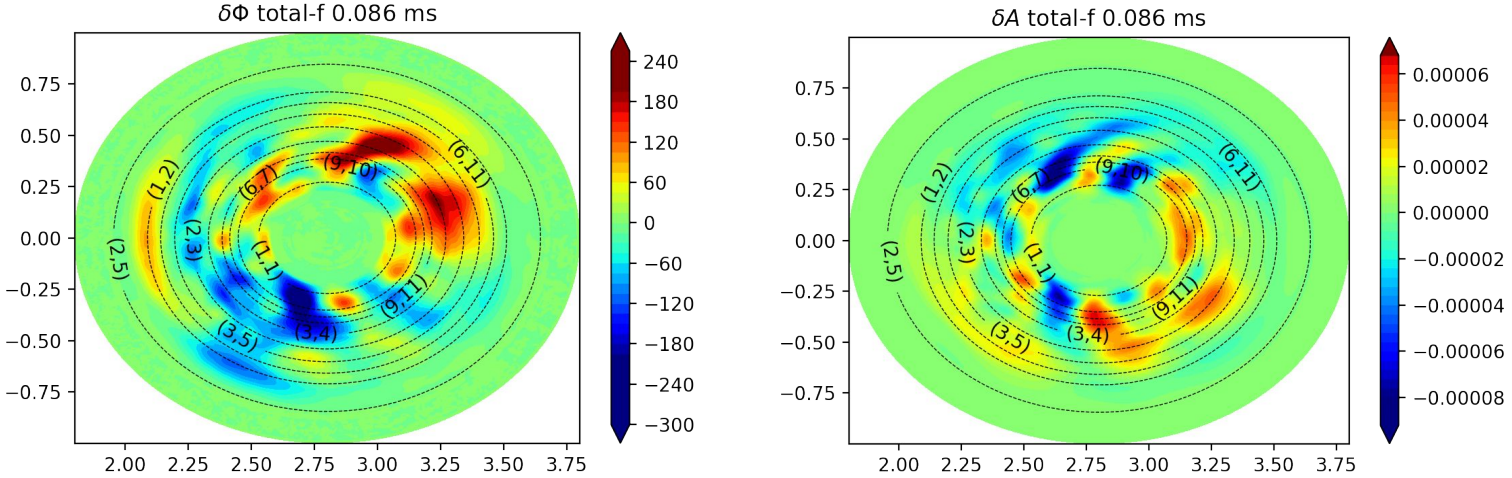
Total-f explicit electromagnetic simulation in the ECBC tokamak plasma showing the electrostatic potential turbulence level as a function of time for all toroidal mode numbers n={1,…}, with low-n modes excited first. Similar quasi-saturation is found for magnetic perturbation modes.

Total-f profile-consistent KBM saturation

Poincaré plot of the KBM turbulence quasi-saturated state: distortion or reconnection of the magnetic field lines around mode rational surfaces can be observed, with many nonlinear modes interacting non-locally across different mode rational surfaces.



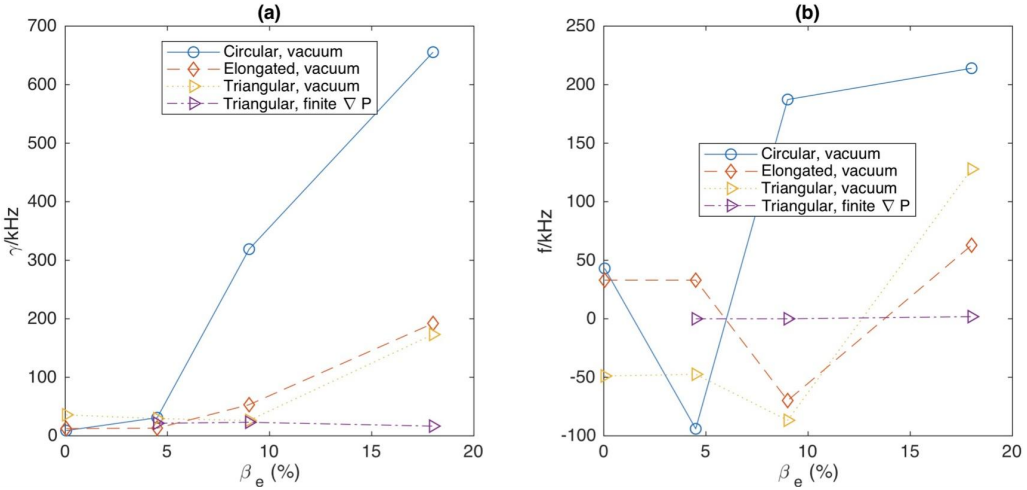
Total-f profile-consistent KBM quasi-saturation



Electrostatic potential (left) and parallel magnetic vector potential (right) in the (*R*,*z*) plane at the KBM turbulence quasi-saturated state. Significant mode rational surfaces are indicated by dotted contours that are labelled with the resonant toroidal (*n*) and poloidal (*m*) mode numbers (*n*,*m*).

KBM stabilization by shaping effects in compact tori

- The explicit EM scheme has been used to study the effects of magnetic geometry in compact tori.
- Geometry comparable to the NSTX spherical tokamak was used, and background density and temperature profiles were based on the CBC.
- For the circular case, as β_e is increased, there are transitions from an ITG mode to a CTEM, and then to a KBM.
- Similar transitions are also observed for the vacuum elongated and triangular cases, although the transitions occur at higher β_e, and, in particular, there is significant stabilization of the KBM for these highly-shaped geometries.
- The β_e scan was repeated for the triangular case with profile-consistent finite-pressure magnetic equilibria: mode transitions were not observed, and this could be due to the absence of compressional magnetic perturbations.



(a) Growth rates and (b) real frequencies as a function of electron plasma β for various compact toroidal geometries.

Conclusion

- Two new EM schemes have been implemented and verified in the global gyrokinetic PIC code XGC.
- Both schemes use gyrokinetic ions and drift-kinetic electrons, and verification was performed against other global gyrokinetic codes.
- One scheme is an implicit scheme that eliminates the cancellation problem, and the other scheme is a computationally efficient explicit scheme that mitigates the cancellation problem.
- The total-f explicit scheme has achieved KBM quasi-saturation and background profile relaxation that is consistent with the source rate.
- In δf mode, the explicit scheme has shown KBM stabilization by shaping effects in compact tori.